Artificial coastal defence structures as surrogate habitats for natural rocky shores: giving nature a helping hand

by

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Barnacle recruits on an engraved disc marking rock pool #10. A serendipitous illustration of the rationale behind my research: increasing habitat complexity increases recruitment of marine life.

As they say, a picture paints a (fifty) thousand words (thesis).

ABSTRACT

Engineered coastal defence structures are proliferating around coastlines globally to protect expanding urban developments from predicted sea level rise and extreme weather events. In response to evolving marine planning policies, it is becoming increasingly necessary to incorporate ecologically-sensitive design into coastal developments, not only to minimise their environmental impacts, but also to maximise potential ecological and socio-economic secondary benefits. I investigated coastal defence structures as surrogate habitats for rocky shore biodiversity, and the potential for the design of structures to be manipulated to achieve more beneficial outcomes. I focused on three major knowledge gaps that must be addressed in order to effectively incorporate ecologically-sensitive design into coastal defences: **(i)** the capacity to predict ecological responses to different engineering designs for coastal defence structures; **(ii)** the potential for ecological engineering interventions to enhance biodiversity on structures; and **(iii)** stakeholder perceptions regarding the desirability of potential secondary benefits that can be built-in to developments. To address the first knowledge gap, I surveyed 125 intertidal coastal defence structures around the coast of Wales, UK, and modelled the relationship between a number of physico-environmental parameters and the biological communities colonising each structure. Using these data I developed a predictive tool and demonstrated that, given the nature of the shoreline on which a new coastal defence was required (i.e. the surrounding sediments and level of exposure to prevailing wind and waves), it would be possible to predict (with up to 62% confidence) the characteristic community that could be expected to colonise a structure, based on its broad shape, position in the intertidal zone, and abundance of microhabitats. To address the second knowledge gap, I explored the potential for a novel ecological engineering intervention (drill-cored artificial rock pools) to enhance biodiversity on an intertidal riprap breakwater. Over a 30-month period, I found that the artificial pools performed an important ecological function on the structure. They were utilised by numerous species that were not otherwise recorded on surrounding emergent rock surfaces, including taxa that have frequently been reported to be absent or scarce on coastal defences previously (e.g. mobile fauna, lower-shore taxa and proportionally-rarer taxa). Furthermore, the artificial pools were just as productive as natural rock pools and supported a comparable number of species. The composition of communities in artificial and natural pools, however, was different, largely on account of differences in sessile assemblages (i.e. algae and encrusting fauna). The intervention, nevertheless, was an effective and affordable means of ecological enhancement, and has received considerable interest from industry and practitioners. To address the third knowledge gap, I investigated stakeholder attitudes regarding desirability of different potential secondary benefits that may be built-in to coastal developments. Although this study revealed complex and nuanced perceptions across sectors, there was unanimous support for implementing *multi-functional* coastal defence structures in place of traditional single-purpose ones, and in general the most desirable secondary benefits were ecological ones (prioritised over social, economic and technical benefits). In this thesis I evaluate these outcomes in the context of their application to marine planning and conservation management. I finally conclude by outlining the steps that are necessary to achieve wide-scale and effective implementation of ecologically-sensitive and multi-functional design for artificial coastal defence structures that are becoming ubiquitous features of urban coastlines globally.

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General Introduction

1.1 Introduction

Globally, artificial structures are proliferating in the marine environment as an adaptational response to anticipated climate change, and to support increasing commercial and recreational use of the sea. Consequently, their potential impacts on the natural environment have become an issue of great concern (see Gill 2005, Govaerts and Lauwaert 2009, Dugan et al. 2011, Mineur et al. 2012, Firth et al. 2013a, Dafforn et al. 2015 for recent reviews). While infrastructure associated with oil and gas exploration (e.g. rigs and platforms), marine renewables developments (e.g. turbine pilings and scour protection), navigation (e.g. docks and buoyage), mariculture (e.g. trestles and enclosures), and recreation (e.g. pontoons and artificial reefs), are all commonplace features in the marine environment, in this thesis I focus on intertidal coastal defence structures (such as breakwaters, groynes and seawalls). Coastal defence structures are proliferating along our coasts to protect expanding urban developments (Small and Nicholls 2003) from predicted sea level rise and extreme weather events (Donat et al. 2011, Young et al. 2011, IPCC 2013). In some parts of Europe (Airoldi and Beck 2007), the U.S. (Davis et al. 2002) and Australia (Chapman and Bulleri 2003), over half of natural shorelines have been replaced or reinforced by artificial hard substrata. In England and Wales, almost 40% of the entire coast has been modified (Masselink and Russell 2013), and additional defence measures are likely to be necessary in the coming years (Koike 1996, Thompson et al. 2002, Govaerts and Lauwaert 2009).

The construction of engineered coastal defences can have considerable impacts on receiving habitats and species (Govaerts and Lauwaert 2009, Dugan et al. 2011). In addition, structures will inevitably be colonised by epibenthic marine organisms, which may have further positive and/or negative implications for the environment and society. I have investigated the role of artificial coastal defence structures as surrogate habitats for marine biodiversity, and the potential for structures to be manipulated to achieve more beneficial secondary outcomes from coastal defence developments. In this introductory chapter I summarise (with examples from around the world) the potential impacts of coastal defence structures on the receiving environment, their performance as habitats for marine biodiversity, the growing interest in ecologically-sensitive design for their construction, and the knowledge gaps that remain preventing progress. This will be discussed in the context of international conservation legislation and translated UK marine management policies, which provide the rationale for this research. Finally, the overall aim and specific objectives of the thesis will be presented.

1.2 Impacts of coastal defence structures on the receiving environment

The negative environmental impacts of engineered coastal defence structures have been the subject of several recent reviews (Airoldi and Beck 2007, Govaerts and Lauwaert 2009, Bulleri and Chapman 2010, Dugan et al. 2011, Dafforn et al. 2015). Coastal defences are often (but not always) introduced to soft sedimentary environments where there tends to be the greatest need for coastal protection. Aside from the inevitable loss of natural habitat directly within the footprint of structures, altered geomorphology, sediment dynamics and water flow can cause losses and disturbance of natural habitats at the local (e.g. Brown and McLachlan 2002, Airoldi et al. 2005a, Martin et al. 2005, Bertasi et al. 2007, Dugan et al. 2008) and regional scales (e.g. Airoldi et al. 2005a, Martin et al. 2005, Seitz and Lawless 2006, Airoldi and Beck 2007). In addition, the novel hard substrate introduced by engineered structures can directly modify environmental conditions for adjacent communities (e.g. Bertasi et al. 2007, Goodsell et al. 2007, Martins et al. 2009) and increase connectivity between isolated hard-bottomed habitats (e.g. Johannesson and Marmoes 1990, Mieszkowska et al. 2005).

1.2.1 Modified local environmental conditions

The ecological impacts of shoreline armouring can be particularly severe and widespread. For example, 74% of San Diego Bay is armoured with hard revetments (Davis et al. 2002). On armoured shores, dry upper-beach zones are lost and mid-beach zones are narrowed (Feagin et al. 2005, Dugan and Hubbard 2006, Dugan et al. 2008). Dugan et al. (2008) reported significantly fewer and smaller upper-intertidal infauna along armoured segments of shore in Santa Barabara, compared with unarmoured segments. They also found important implications for foraging and roosting birds.

Further down in the intertidal and shallow subtidal zone, a European-wide study of the effects of low-crested coastal defence structures found consistent alteration to adjacent soft-bottom macroinvertebrate communities (Martin et al. 2005). Assemblages in sediments around breakwaters were markedly different to control assemblages on shores without breakwaters. Further, infaunal assemblages on the seaward exposed sides of structures were different to those on the landward sheltered sides (see also Bertasi et al. 2007, Walker et al. 2008). This influence of artificial sheltering of open-coast habitats also appeared to be responsible for an observed shift from consumer- to producer-dominated communities on a rocky shore behind a breakwater in the Azores (Martins et al. 2009). Rocky shores ‘fragmented’ by seawalls in Sydney Harbour were also found to support less diverse communities than naturally-patchy rocky shores surrounded by natural habitats (Goodsell et al. 2007). Shading from infrastructure, such as piers and seawalls, has been linked to reduced density of salt marsh plants in South Carolina (Sanger et al. 2004), altered composition of epibenthic assemblages in Sydney Harbour (Glasby 1999, Blockley 2007, Marzinelli et al. 2011), and depauperate assemblages of juvenile fish in the Hudson river (Able et al. 1998). Coastal fish assemblages can also be influenced by the presence of submerged (Scyphers et al. 2015; but see Clynick 2006) and intertidal (Martin et al. 2005) breakwaters, probably as a result of introduced refuge habitat (Martin et al. 2005) and food sources (Caine 1987, Perkol-Finkel et al. 2012).

1.2.2 Increased connectivity

By increasing connectivity between isolated hard-bottomed communities, artificial structures can facilitate species range expansions, having knock-on implications for population genetics (Kimura and Weiss 1964, Johannesson and Marmoes 1990, Becker et al. 2007, Fauvelot et al. 2009, Rius et al. 2014, Adams et al. 2014). For example, artificial breakwaters in Belgium enabled the periwinkle *Littorina saxatilis* to spread along sedimentary coastlines, despite lacking a planktonic larval stage (Johannesson and Marmoes 1990). Along the south coast of England, southern warm-adapted species of gastropods and barnacles have breached natural hydrographic barriers, apparently via coastal defence 'stepping stones' (Mieszkowska et al. 2005, Hawkins et al. 2008, 2009, Firth et al. 2013a). Glasby and Connell (1999) also described the stepping stone effect of urban structures connecting different habitats in Sydney Harbour, and Adams et al. (2014) modelled the role of novel habitat stepping stones associated with offshore renewables developments in the spread of intertidal organisms around Scotland. It has been suggested that artificial structures may provide opportunities for assisted migration of species at risk from climate change (Hoegh-Guldberg et al. 2008). However, the negative implications of urban sprawl becoming one of the main drivers of biological homogenisation at local, regional and global scales, may outweigh any potential positive effects (Kühn and Klotz 2006, McKinney 2006).

Artificial structures in the marine environment are often colonised by opportunistic and weedy species that take advantage of the unexploited bare substrata, and the novel materials, surface inclinations, shelter and shading (e.g. Bulleri and Airoldi 2005, Tyrrell and Byers 2007, Vaselli et al. 2008, Marzinelli et al. 2011, Dafforn et al. 2012; but see Pister 2009). As a result, coastal defence structures have been widely reported to facilitate the spread of non-native and invasive species (Bulleri and Airoldi 2005, Ruiz et al. 2009, Mineur et al. 2012, Rius et al. 2014, Airoldi et al. 2015). In the Mediterranean, structures introducing 'unnatural' sheltered rocky habitat along exposed open coasts provided opportunities for non-native algal and ascidian species to colonise (Bulleri and Airoldi 2005, Vaselli et al. 2008, Airoldi and Bulleri 2011, Airoldi et al. 2015). This was exacerbated by disturbance events such as structural maintenance and recreation (Bulleri and Airoldi 2005, Airoldi and Bulleri 2011; see also Bracewell et al. 2013). Structures in close proximity to transport infrastructure, such as ports and harbours, are particularly susceptible to colonisation of non-indigenous species, particularly encrusting invertebrates and ascidians (Gollasch 2002, Floerl and Inglis 2003, Lambert and Lambert 2003, Glasby et al. 2007, Griffith et al. 2009, Dafforn et al. 2009, Rius et al. 2014, Airoldi et al. 2015).

1.3 Coastal defence structures as habitats

Any new hard substrata introduced to the marine environment will inevitably be colonised by fouling and epibenthic marine organisms. This gives rise to potential secondary functions of artificial structures as habitat-providers in the marine environment. It has been well-documented that intertidal coastal defences typically support organisms normally found on nearby rocky shores (Southward and Orton 1954, Hawkins et al. 1983, Chapman 2003, Chapman and Bulleri 2003, Pinn et al. 2005, Moschella et al. 2005, Firth et al. 2015b), but that the colonising assemblages are often not completely analogous. Hence, Moschella et al. (2005) described coastal defence structures as poor imitations of (*ersatz*) rocky shores. In particular, there is growing evidence that artificial structures support lower diversity (Chapman 2003, Pinn et al. 2005, Moschella et al. 2005, Pister 2009, Firth et al. 2013b, 2015b, Aguilera et al. 2014) and different relative abundances of taxa (Chapman and Bulleri 2003, Knott et al. 2004, Pinn et al. 2005, Moschella et al. 2005, Pister 2009), compared with adjacent natural rocky habitats.

The diversity deficit reported in different studies has been attributed to various different groups of taxa. For example, Chapman (2003) reported a paucity of mobile fauna and proportionally-rarer taxa on the seawalls that comprise over 50% of the shoreline in Sydney Harbour. Only around half of the mobile animals found on adjacent natural shores were recorded on the walls – several species of gastropods and echinoderms were absent. Pister (2009) and Aguilera et al. (2014) also found lower diversity of mobile species on riprap boulder structures than on natural shores, in southern California and northern Chile, respectively. Pister (2009), however, warned that sampling methods may easily under-estimate proportionally-rarer and mobile taxa that inhabit the interstitial spaces within riprap structures. Others have attributed the diversity deficit to a lack of lower-shore and desiccation-sensitive taxa (Moschella et al. 2005, Firth et al. 2015b). These observations may be explained largely by the typically-low habitat complexity of coastal defence structures, compared with natural shores (Chapman 2003, Moschella et al. 2005, Aguilera et al. 2014, Firth et al. 2015b). At the finest scale of complexity (<1 cm), materials frequently used for coastal engineering (e.g. quarried granite and concrete) often have smoother surface texture than rocky shore substrata. At small (1 – 100s cm) and medium (1 – 100s m) scales, they tend to be relatively homogeneous in terms of habitat shape and structure, lacking important microhabitats such as rock pools and crevices. Surface composition can influence recruitment of marine organisms (Johnson 1994, Carl et al. 2012, Bracewell et al. 2012, Green et al. 2012, Coombes et al. 2015), and microhabitats are known to be extremely important for intertidal biodiversity, retaining moisture and providing refuge from predation and physical disturbance (Raffaelli and Hughes 1978, Fairweather 1988, Metaxas and Scheibling 1993, Gray and Hodgson 1998, Johnson et al. 1998, 2003, Firth et al. 2013b, 2014a, Aguilera et al. 2014).

Pister (2009) suggested that wave exposure may also have contributed to differences between intertidal artificial and natural habitats in California (see also Davis et al. 2002). Where structures are introduced to high-energy sedimentary environments (as coastal defences often are), high disturbance regimes from wave energy and sand scouring (Moschella et al. 2005, Burcharth et al. 2007, Firth et al. 2014b) may preclude colonisation of particular species (e.g. certain gastropods: Boulding 1993; and macroalgae: Jonsson et al. 2006), and prevent communities from developing beyond early-successional stages. Disturbance from anthropogenic activities, such as recreational harvesting (Bacchiocchi and Airoldi 2003, Airoldi et al. 2005b) and engineering maintenance (Bacchiocchi and Airoldi 2003, Moschella et al. 2005, Airoldi and Bulleri 2011), have also been implicated in this phenomenon. Even when subject to the same local wave climate, it is possible that the wave-generated forces experienced by organisms on artificial structures may be greater than those exerted on adjacent natural rocky shores, on account of reduced dissipative surf zone widths and steeper surface inclinations (Burcharth and Hughes 2006, Pister 2009). Conversely, structures with both exposed and leeward sides may present ‘unnatural’ sheltered habitat along exposed open coasts, which may favour algal-dominated communities (Southward and Orton 1954, Jenkins et al. 1999, Jonsson et al. 2006) or, as described above, promote opportunistic and invasive species (Bulleri and Airoldi 2005, Vaselli et al. 2008, Airoldi and Bulleri 2011, Airoldi et al. 2015).

Several other factors may lead to different communities in artificial and natural habitats. For example, surface orientation, inclination and shading may influence biodiversity on vertical or overhanging structures, such as seawalls and pilings (Glasby 1999, Connell 1999, Glasby and Connell 2001, Knott et al. 2004, Chapman and Blockley 2009, Marzinelli et al. 2011, Chapman and Underwood 2011), leading to different communities to natural reef habitats (but see Firth et al. 2015b). On intertidal structures, a steeper shore profile is likely to also lead to a reduction in habitat extent compared with natural shores (Moschella et al. 2005, Chapman and Underwood 2011), which may limit species diversity and abundance as a simple product of species-area relationships (Hawkins and Hartnoll 1980). Artificial structures isolated from natural hard substrata may not be colonised by species with limited dispersal capabilities (e.g. some coralline algae and fauna with no planktonic phase: Dethier et al. 2003, see also Davis et al. 2002, Evans et al. 2015), leading to absences of taxa that are common in natural habitats. Furthermore, communities colonising isolated structures surrounded by soft sediments may be subject to increased biotic disturbance from predators and herbivores attracted to these 'oasis' habitats (Perkol-Finkel et al. 2012, Ferrario 2013).

1.4 Environmental management and policy context

In addition to the potential environmental impacts and poor habitat quality of artificial structures described above, 'hard' coastal defence approaches are often extremely expensive, encourage inappropriate coastal development along eroding or low-lying coasts, and exacerbate coastal erosion through 'coastal squeeze' of natural intertidal habitats (Brown and McLachlan 2002, Turner et al. 2007, Govaerts and Lauwaert 2009). Consequently, 'soft' engineering approaches, such as beach replenishment, sand dune stabilisation and managed realignment, are widely considered to be more sustainable options for flood and coastal erosion risk management (Capobianco and Stive 2000, Turner et al. 2007, Govaerts and Lauwaert 2009, Temmerman et al. 2013, Hanley et al. 2014). Nevertheless, in scenarios where no alternative options are viable for protecting people and assets, shoreline management plans (SMPs) continue to recommend a strategy of 'hold the line' (Environment Agency 2009). This means that local authorities will be required to maintain existing defences and potentially implement additional 'hard' protection measures.

In order to fulfil international marine conservation commitments (e.g. those laid out in the OSPAR Convention and the Convention on Biological Diversity; also see Naylor et al. 2012 for an outline of relevant European and UK legal instruments), governments have begun to recognise the need for more proactive marine planning policies and legislation. The UK's Marine Policy Statement (HM Government 2011) advises that, in addition to "*avoid*[ing] *harm to marine ecology* [and] *biodiversity*" (§2.6.1.3), marine and coastal developments also "*may provide, where appropriate, opportunities for building-in beneficial features*" (§2.6.1.4). Although not prescribing a definitive obligation, this clearly advocates sensitive engineering design that can deliver secondary benefits above and beyond the primary purpose of developments (i.e. in the context of this thesis, coastal protection). In response, there is growing scientific interest in novel multi-functional coastal defence structures that can deliver secondary ecological and/or socio-economic benefits, thus supporting drivers for sustainable development (Challinor and Hall 2008; see also Zanuttigh et al. 2015). It is important to recognise, however, that ecological secondary benefits that can be built-in to engineered structures are unlikely to mitigate or compensate for the loss of natural habitats and species caused by their construction. The provision of secondary benefits should not, therefore, be considered of *net* benefit to the natural environment and should not be prioritised over more sustainable options for flood and coastal erosion risk management.

In the context of this thesis, I consider a 'built-in beneficial feature' to be some quantifiable enhancement of the ecological condition of an artificial structure (e.g. increased species diversity, increased abundance of species of conservation value), relative to its condition *without* that built-in feature. Where hard defence structures are considered appropriate and necessary for managing risks of flooding and erosion, opportunities must be taken to maximise ecological benefits as well as to minimise environmental impacts.

1.5 Knowledge gaps for implementing ecologically-sensitive design

Despite a clear policy recommendation (HM Government 2011), there are few examples of truly and purposefully-designed multi-functional coastal defence developments around the world (but see Harris 2003, Jackson et al. 2012, Mendonça et al. 2012, Scyphers et al. 2015), particularly ones intended to deliver ecological benefits (Harris 2003, Scyphers et al. 2015). Extensive review of current literature revealed several clear knowledge gaps that must be addressed in order to effectively incorporate ecologically-sensitive design into coastal defence developments, in order to minimise environmental impacts and maximise ecological secondary benefits.

1.5.1 Predictive capability

Effective evaluation of the ecological outcomes that may be expected from different options for coastal defence design requires reliable prediction of the biological communities that will colonise different types of structures in different locations. As discussed above, several studies have described the different communities colonising coastal defence structures in various places (e.g. Southward and Orton 1954, Davis et al. 2002, Chapman 2003, Chapman and Bulleri 2003, Bulleri et al. 2005, Moschella et al. 2005, Pister 2009, Firth et al. 2013b, 2015b). Although some common rocky shore taxa (e.g. barnacles and opportunistic green algae) can be reliably expected to colonise any new hard structure in the marine environment (Sousa 1979, Moschella et al. 2005), the overall composition of communities is likely to be determined by a number of physical design features and environmental factors operating at different spatial scales. For example, their position in the intertidal zone would largely determine the species that were able to colonise different structures (Foster 1971, Raffaelli and Hawkins 1996). Similarly, the choice of construction material and the physical complexity of structures would be likely to influence recruitment and subsequent community development (Johnson 1994, Chapman and Blockley 2009, Firth et al. 2014b, Browne and Chapman 2014, Coombes et al. 2015, Evans et al. 2015, Perkol-Finkel and Sella 2015). The suitability of conditions for different species may also be influenced by other physical and environmental factors. For example, high exposure to wave energy may favour certain species (Mullineaux and Garland 1993, Moschella et al. 2005, Vaselli et al. 2008) but hinder settlement and post-settlement survival of others (Mullineaux and Garland 1993, Boulding and Van Alstyne 1993, Jonsson et al. 2006, Perkol-Finkel et al. 2012). Further, the composition of the surrounding habitat would determine the proximity of source populations as well as the degree of disturbance from scour action and sedimentation (Moschella et al. 2005).

Despite the wealth of theoretical and observational evidence of how physical and environmental factors can influence biological community development, the complexity of interactive processes (Menge and Sutherland 1987, Benedetti-Cecchi

2000) and high levels of natural variability in recruitment regimes (Underwood and Fairweather 1989, Burrows et al. 2010) make it difficult to accurately predict the full communities that will colonise new coastal defence structures. Whilst many of the studies discussed here have focused on describing patterns and species distributions on coastal defences, to date, little attention has been given to understanding the ecological processes operating in these artificial habitats, which may not be the same as those operating in natural habitats (e.g. Jackson et al. 2008, Klein et al. 2011, Firth et al. 2013b; also discussed by Chapman and Underwood 2011). Further, post-construction monitoring of communities colonising coastal defences has rarely been implemented, meaning that opportunities to understand the ecological implications of developments (and potential future developments) have been missed (Airoldi et al. 2005a). Practitioners and academics are urging a move beyond descriptive studies, to develop the capacity to predict the ecological responses that are likely to result from different engineering designs (Bohnsack and Sutherland 1985, Airoldi et al. 2005a, Bulleri and Chapman 2010, Chapman and Underwood 2011, Hulme 2014).

1.5.2 Potential for ecological engineering

As discussed above, several studies have attributed low biodiversity on coastal defence structures to their typically-low topographic complexity (Chapman 2003, Moschella et al. 2005, Aguilera et al. 2014, Firth et al. 2015b). Moschella et al. (2005) suggested that species diversity may be increased on artificial structures through engineering interventions, and that the scope for such interventions is greatest at the microhabitat scale (1 – 100s cm). Subsequent experimental trials recommended that settlement and survival could be maximised by incorporating multiple novel habitats with a variety of depths and diameters (from the 10 m to <1 cm scale: Firth et al. 2014b). As a consequence, there is currently much interest in the concept of 'ecological engineering' (Firth et al. 2013a) to develop novel designs for coastal defence structures that incorporate more heterogeneous microhabitats.

Small pits and crevices are important microhabitats for rocky shore biota, providing shade, moisture and refuge from predation and disturbance (Fairweather 1988, Gray and Hodgson 1998, Johnson et al. 1998, 2003). The addition of pits and crevices to artificial structures can be an effective way of increasing local species richness (Firth et al. 2014b) and enhancing stocks of exploited species (Martins et al. 2010) on structures. However, the addition of microhabitat complexity at this small scale may have a limited effect on biodiversity if they are rapidly occupied by already-abundant mobile fauna or larval settlement events, and thus unavailable for colonisers that arrive later in the successional trajectory (Chapman and Underwood 2011). Browne and Chapman (2014) therefore suggested that engineering interventions modelled on small- and medium-sized rock pools may be more likely to support persisting trends in increased diversity. It should be acknowledged, however, that although diversity may be increased on the artificial structures themselves, regional-scale biodiversity may not necessarily be enhanced if interventions simply provide additional habitat for already locally-abundant taxa, or for species that would not naturally occur in the area (this may in fact be considered a negative change at the regional scale). In the context of this thesis, I refer to biodiversity enhancement primarily in terms of the effect of an intervention on the community colonising an artificial structure, relative to the community that would be colonising the structure *without* the intervention. There are several ways in which communities may be considered to be 'enhanced' (e.g. increased diversity, increased primary production, reduced abundance of non-native species, etc.). The relative merits of each would depend on the local environment and specific management objectives for a development (see below and Chapter 4 for further discussion).

Through collaborations with engineers, water-retaining features mimicking rock pools were added to vertical seawalls in Sydney Harbour, both during construction (i.e. shaded recesses with water-retaining lips: Chapman and Blockley 2009) and retrospectively (i.e. concrete flower pots bracketed to walls: Browne and Chapman 2014). These engineered habitats were colonised by a variety of intertidal organisms and were found to be easy, cost-effective ways of enhancing the ecological condition of vertical seawalls. However, both designs had limitations: the shaded recesses may not provide suitable habitat for the full range of intertidal taxa since they are continually shaded; and several of the flower pots were lost from the walls within seven months of deployment. It is also unlikely that these novel habitats would perform in the same way on other types of artificial structures in other locations. Habitat enhancement interventions intended for coastal defence schemes should be robust against disturbance from extreme weather events in exposed environments. Sydney Harbour is a semi-enclosed environment with a relatively small tidal range, unlike the exposed open shorelines where coastal defence structures are frequently required. Therefore, there remains a need for additional long-term, fully-replicated trials to determine the potential biodiversity benefits of different types of water-retaining features that can be incorporated in both new and existing coastal defence structures.

1.5.3 Desirability of potential secondary benefits

The lack of implementation of multi-functional coastal defence structures to date may be partly because of ineffectual science-policy linkages (McNie 2007, Holmes and Clark 2008, Weichselgartner and Kasperson 2010). There is increasing policy-maker recognition of the need to incorporate ecologically-sensitive design into new developments (HM Government 2011, USACE 2012), and there is growing evidence that engineering interventions can enhance the ecological condition of artificial structures (e.g. Chapman and Blockley 2009, Martins et al. 2010, Perkol-Finkel et al. 2012, Browne and Chapman 2014, Firth et al. 2014b, Evans et al. 2015, Perkol-Finkel and Sella 2015). Yet there is no clear policy steer regarding desirable outcomes from ecological enhancement interventions for coastal defence developments (Moschella et al. 2005, Chapman and Underwood 2011, Firth et al. 2013a).

It is unlikely that secondary benefits built-in to coastal defences would be perceived in the same way across different stakeholder groups, e.g. conservation groups, engineers, statutory bodies and researchers (Naylor et al. 2012; see also Zanuttigh et al. 2015). Further, their order of priority when evaluating different design options is unlikely to be consistent, since each option would present a suite of compromises and trade-offs. For example, the addition of pits, crevices and rock pools to artificial structures may be an effective way of increasing localised biodiversity on structures (Chapman and Blockley 2009, Firth et al. 2014b, Browne and Chapman 2014, Evans et al. 2015) and stocks of exploited species (Martins et al. 2010), but they may not support the same assemblages of marine life as they do in natural systems (Evans et al. 2015). Similarly, species of conservation interest can be transplanted onto structures (Clark and Edwards 1994, Perkol-Finkel et al. 2012, Ferrario 2013, Ng et al. 2015), but this may have implications for local authorities tasked with maintaining those structures (Airoldi and Bulleri 2011). Furthermore, reefs that aggregate commercial fisheries species may benefit professional and/or recreational fisheries (Collins et al. 1994) but may lead to expedited over-exploitation if structures attract individuals from surrounding natural habitats rather than produce additional biomass (Pickering and Whitmarsh 1997).

Habitat interventions may be designed with specific ecological and socio-economic responses in mind, but planners are required to judge the relative merits of each response in order to select the optimal design. To ensure research efforts and resources are invested effectively, it is necessary to determine what secondary benefits can potentially be built-in to engineered coastal defence structures, and further, which of these benefits would be most desirable.

1.6 Aim and objectives

The overall aim of my research was to investigate artificial coastal defence structures as surrogate habitats for rocky shore biodiversity, and the potential for the design of structures to be manipulated to achieve more beneficial outcomes. More specifically, I identified three major knowledge gaps that must be addressed in order to effectively incorporate ecologically-sensitive design into coastal defence developments, in order to minimise environmental impacts and maximise secondary ecological benefits. These were: (i) the capacity to predict ecological responses to different engineering designs for coastal defence structures; (ii) the potential for ecological engineering interventions to enhance biodiversity on structures; and (iii) stakeholder perceptions regarding the desirability of potential secondary benefits that can be built-in to developments.

To address the need to develop predictive capabilities for evaluating different engineering options for coastal defences, I developed a statistical model with the potential to predict ecological responses to different designs, using empirical field observations (Chapter 3). Coastal defence structures were surveyed around the coast of Wales, UK, to collate a catalogue of environmental (e.g. exposure, surrounding habitat) and physical (e.g. material, shape, orientation) attribute data, along with the characteristic biological communities colonising each structure. Using a variety of multivariate techniques, a demonstration tool was developed, with the power to predict the communities that would colonise a new structure, according to a parsimonious group of physico-environmental predictor variables. The tool was evaluated in the context of its application for informing engineering and planning decisions for new marine and coastal developments.

To explore the potential for ecological engineering as a means of enhancing biodiversity on coastal defence structures, I trialled drill-cored artificial rock pools on an intertidal riprap breakwater in Wales, UK (Chapter 2). Their potential to increase biodiversity on the breakwater, and to provide surrogate habitat for rocky shore communities, was evaluated. The effect of depth and timing of installation was assessed, as was the likelihood that results would be replicated from one year to the next. The artificial rock pools were evaluated in the context of their application for habitat enhancement of both new and existing coastal defences.

To investigate stakeholder attitudes regarding the desirability of potential secondary benefits that can be built-in to coastal defence developments, I carried out a perception study in England and Wales using two different survey techniques: a traditional quantitative questionnaire method and a semi-quantitative Delphi method (Dalkey 1969) (Chapter 4). The surveys explored stakeholder perceptions and priorities regarding the most important considerations for planning coastal defence developments, the potential secondary benefits that can be built-in to developments, and the level of support for implementing multi-functional coastal defences. Differences and consensus in perceptions across different sector groups were identified, along with the current barriers to effective implementation.

The general discussion (Chapter 5) synthesises the outcomes of my research and the implications for marine planning and conservation management. In particular, the applied 'impact' of the artificial rock pool enhancements, which have received considerable attention from the construction industry and statutory bodies, is discussed. Limitations and remaining knowledge gaps are identified and recommendations for further research are made. Similarly, actions for refining the predictive modelling tool are proposed. Finally, I outline the steps that are needed to overcome the barriers to effective implementation of ecologically-sensitive and multi-functional design for artificial coastal defence structures that are becoming ubiquitous features of urban coastlines globally.

CHAPTER TWO

Predicting the ecological response to engineering options for artificial structure design

Abstract

Artificial coastal defence structures (such as breakwaters, groynes and seawalls) are proliferating around urban coastlines globally as an adaptational response to rising and stormier seas. In certain scenarios there may be scope, within technical and financial constraints, for several alternative engineering designs to be considered and evaluated on the basis of predicted environmental outcomes. Effective evaluation of alternatives requires reliable prediction of the biological communities that will colonise different types of structures in different locations. Despite the wealth of theoretical and observational evidence of how physical and environmental factors can influence biological community development, however, the complexity of interactive effects and high levels of natural variability in recruitment regimes make it difficult to accurately predict the full communities that will colonise new structures. Practitioners and academics alike are urging researchers to develop the capacity to predict the ecological responses that are likely to result from different engineering designs. In this study we surveyed 125 artificial intertidal structures around the coast of Wales, UK, and collated a catalogue of environmental (e.g. exposure, surrounding habitat) and physical (e.g. material, size, shape) parameters, along with the biological communities colonising each structure. Using a variety of multivariate statistical techniques we developed a predictive model and demonstrated that, given the nature of the shoreline on which a new coastal defence was required (i.e. the surrounding sediments and level of exposure to prevailing wind and waves), it would be possible to predict the characteristic community that could be expected to colonise a structure, based on its broad shape, position in the intertidal zone, and abundance of microhabitats. The model was able to correctly predict broad community structure with 62% allocation success. The success rate was reduced, however, when attempting to predict finer detail in community characteristics. This first attempt to predict colonisation based on empirical observations demonstrated potential as an effective management tool for environmentally-sensitive design of coastal defence developments. This predictive capability will be essential to mitigate ecological impacts and maximise the potential secondary benefits that can be built-in to engineered developments in future.

2.1 Introduction

Artificial coastal defence structures, such as breakwaters, groynes and seawalls, are prominent features of urban coastlines globally (e.g. Koike 1996, Davis et al. 2002, Chapman and Bulleri 2003, Airoldi and Beck 2007). With the primary objectives of defending the coast and protecting people and assets, these structures can serve a number of specific functions, including stabilising beach sediments, absorbing wave energy, and creating sheltered harbours. Depending on the specific function required, available resources, the nature of the surrounding environment and the vulnerability of the coastline, there are a number of different designs that can be employed for coastal defence developments (Govaerts and Lauwaert 2009). For example, vertical or sloping walls are constructed to shelter harbours and to reinforce shoreline infrastructure; shore-parallel breakwaters of consolidated units (i.e. quarried riprap boulders or moulded concrete dolosse) are used to attenuate wave energy and accumulate sediments; and perpendicular groynes of various shapes and sizes are used for beach stabilisation. Large coastal defence developments often incorporate a number of different types of structures to achieve the overall objectives of the scheme (e.g. Atkins 2009).

Coastal defence developments are subject to Environmental Impact Assessment (EIA; e.g. EC Directive 97/11/EEC) to consider the net impact of all aspects of the development, including sourcing and transportation of materials, construction and maintenance activities, as well as impacts caused by the structures in operation (Govaerts and Lauwaert 2009). In certain scenarios there may be scope, within technical and financial constraints, for several alternative design options to be considered and evaluated on the basis of their environmental impacts. Operational impacts tend to be assessed in terms of loss or disturbance of habitats and species, directly within the footprint of the development (e.g. Dugan et al. 2008) and also at the regional scale as a result of altered geomorphology (e.g. Martin et al. 2005). Attention is rarely given in advance, however, to the communities that will colonise the structures themselves and their potential to positively or negatively impact the wider environment and society (e.g. see environmental assessments by Atkins 2009, Royal Haskoning 2009, 2014; see also Airoldi et al. 2005a). Since artificial structures are known to provide relatively poor-quality intertidal habitats (Chapman 2003, Chapman and Bulleri 2003, Moschella et al. 2005, Firth et al. 2013b, 2015b, Aguilera et al. 2014), recently-updated marine planning legislation recommends consideration of ecological enhancement opportunities for new developments, beyond minimising impacts (e.g. HM Government 2011). In response there is increasing interest in 'green engineering' solutions to enhance the ecological condition of artificial coastal structures, either to support target species (Martins et al. 2010, Perkol-Finkel et al. 2012) or to encourage more natural or diverse communities to colonise (Chapman and Blockley 2009, Firth et al. 2014b, Browne and Chapman 2014, Evans et al. 2015, Perkol-Finkel and Sella 2015). Therefore, the evaluation of different design options for coastal defence developments will increasingly require reliable prediction of the biological communities that will colonise different types of structures, with or without enhancement interventions.

Several previous studies have described the different communities colonising intertidal coastal defence structures in various locations (e.g. Southward and Orton 1954, Davis et al. 2002, Bulleri et al. 2005, Moschella et al. 2005, Firth et al. 2013b, 2015b). Although some common rocky shore taxa (e.g. barnacles and opportunistic green algae) can be reliably expected to colonise any new hard structure in the marine environment (Sousa 1979, Moschella et al. 2005), the overall composition of communities is likely to be determined by a number of physical design features and environmental factors operating at different spatial scales. For example, structures that provide more complex habitats (e.g. rough surface texture, high microhabitat diversity or macro-scale rugosity) are likely to support more diverse communities than simple/uniform structures (Chapman and Blockley 2009, Firth et al. 2014b, Browne and Chapman 2014, Evans et al. 2015, Perkol-Finkel and Sella 2015), because of enhanced settlement potential (Johnson 1994, Carl et al. 2012, Coombes et al. 2015) and niche availability (Pianka 2000, Johnson et al. 2003). Similarly, structures that span the vertical shore gradient, and have both exposed and leeward aspects, offer a wider range of habitat conditions than those limited to a single shore height/aspect, and so may also be expected to support more diverse (but possibly less 'natural': Southward and Orton 1954, Bulleri and Airoldi 2005, Airoldi and Bulleri 2011) communities. It is over-simplistic, however, to assume that (for example) all riprap breakwaters would support the same communities, or that they would support more diverse communities than all vertical seawalls, despite being more rugose at the macro-scale (i.e. with more variety in surface orientation and shaded refuge between boulder units). It may be reasonable to expect that they would support *different* communities to seawalls, in light of the influence of surface inclination (Connell 1999, Knott et al. 2004, Chapman and Underwood 2011) and shading (Glasby 1999, Chapman and Blockley 2009, Marzinelli et al. 2011) on community development, but the relative importance of each element of habitat complexity for biodiversity is unclear (Beck 2000, Johnson et al. 2003, Loke et al. 2015). A vertical seawall with a rough surface texture and high microhabitat heterogeneity (e.g. holes and crevices of different sizes) may support more diversity than a smooth granite breakwater with higher macro-scale complexity (i.e. surface relief). Further, environmental factors beyond the physical engineering design may also affect the colonisation and community development on different structures in different locations. In particular, high exposure to wave energy may favour certain species (Mullineaux and Garland 1993, Moschella et al. 2005, Vaselli et al. 2008) but hinder settlement and post-settlement survival of others (Mullineaux and Garland 1993, Boulding and Van Alstyne 1993, Jonsson et al. 2006, Perkol-Finkel et al. 2012), and the composition of the surrounding habitat would determine the proximity of source populations as well as the degree of disturbance from scour action and sedimentation (Moschella et al. 2005).

Despite the wealth of theoretical and observational evidence of how physical and environmental factors can influence biological community development, the complexity of interactive effects (Menge and Sutherland 1987) and high levels of natural variability in recruitment regimes (Underwood and Fairweather 1989, Burrows et al. 2010) make it difficult to accurately predict the full communities that will colonise new coastal defence structures. Indeed, Greene and Schoener (1982) described ecological succession in the marine environment as a 'fixed lottery'. Further, it has been shown that ecological theories about patterns and processes in natural habitats do not always apply in artificial habitats (Jackson et al. 2008, Klein et al. 2011, Firth et al. 2013b). Practitioners and academics are urging a move beyond descriptive studies, to develop the capacity to predict the ecological responses that are likely to result from different engineering designs (Bohnsack and Sutherland 1985, Airoldi et al. 2005a, Bulleri and Chapman 2010, Chapman and Underwood 2011, Hulme 2014).

The aim of this study was to investigate the potential to predict the characteristic biological communities that would colonise different types of artificial structures in different locations, using empirical field observations of existing structures. We surveyed 125 intertidal coastal defences around the coast of Wales, UK, and collated a catalogue of environmental (e.g. exposure, surrounding habitat) and physical (e.g. material, shape, orientation) parameters, along with the identities and abundances of species colonising each structure. We characterised the different *types* of communities colonising structures based on their multivariate species compositions. Using a variety of multivariate techniques, we then modelled the relationship between the multiple physico-environmental predictor variables and the ecological community response data. We then developed a demonstration tool with the power to predict the characteristic community that would be expected to colonise a new structure, according to a parsimonious group of predictor variables. This was done three times using 'Broad', 'Medium' and 'Fine' scales of definition in the community characterisation (i.e. different levels of detail in the identities and relative abundances of species comprising each type of community). This was to explore the level of detail in community composition that may be discriminated by the predictive tool being developed. Depending on the management objectives and/or mitigation requirements of a development, it may be sufficient to predict only the broad characteristics of the community that will colonise in response to different engineering options. If, however, developers are required to provide habitat for target species (or to discourage undesirable species from colonising) then the capacity to predict finer detail in predicted community composition may be necessary. Here we demonstrate the potential for this statistical approach to be used to develop a management tool for predicting the ecological response to different design options available to engineers. Such a tool would be invaluable for informing engineering and planning decisions for new marine and coastal developments.

2.2 Materials and methods

2.2.1 Field survey

An extensive field survey was undertaken between July and September 2013. One hundred and twenty five intertidal coastal defence structures were surveyed at 55 locations around the coast of Wales, UK (Table 2.1, Figure 2.1). The term ‘structure’ is used here to refer to an individual simple coastal defence (e.g. a wooden groyne) or an individual component of a complex coastal defence (e.g. the scour defence component of a harbour complex comprising a harbour wall and scour defence). Six different types of coastal defence structures were encountered, defined for the purpose of this study as follows: ‘Breakwaters’ (i.e. shore-parallel structures composed of consolidated units; e.g. Figure 2.2a); ‘Groynes’ (i.e. shore-perpendicular structures intended to stabilise beach materials; e.g. Figure 2.2b); ‘Harbour walls’ (i.e. solid shore-parallel walls with a leeward harbour; e.g. Figure 2.2c); ‘Revetments’ (i.e. consolidated units backing a shore; e.g. Figure 2.2d); ‘Scour defence’ (i.e. rubble or boulder scour protection at the foot of harbour walls; e.g. Figure 2.2e); and ‘Seawalls’ (i.e. solid walls backing a shore; e.g. Figure 2.2f). Where multiple structures were present in one location, only unique structures (in terms of their physical parameters, i.e. shape, lowest shore height, material, etc.; Table 2.2) were surveyed. Duplication of parameter-combinations within locations was avoided in order to minimise the influence of spatial autocorrelation.

For each structure, physical and environmental information was recorded for 13 predictor variables (Table 2.2) and the relative abundances of all taxa encountered during a 20-minute search were recorded on the semi-quantitative SACFORN scale (i.e. S = Super Abundant, A = Abundant, C = Common, F = Frequent, O = Occasional, R = Rare, N = Not recorded; Hiscock 1996; Appendix I). Taxa were recorded to species level, but where this was not possible, consistent morphotaxa were used, e.g. ‘Lithothamnia’ for all calcareous crust species combined.

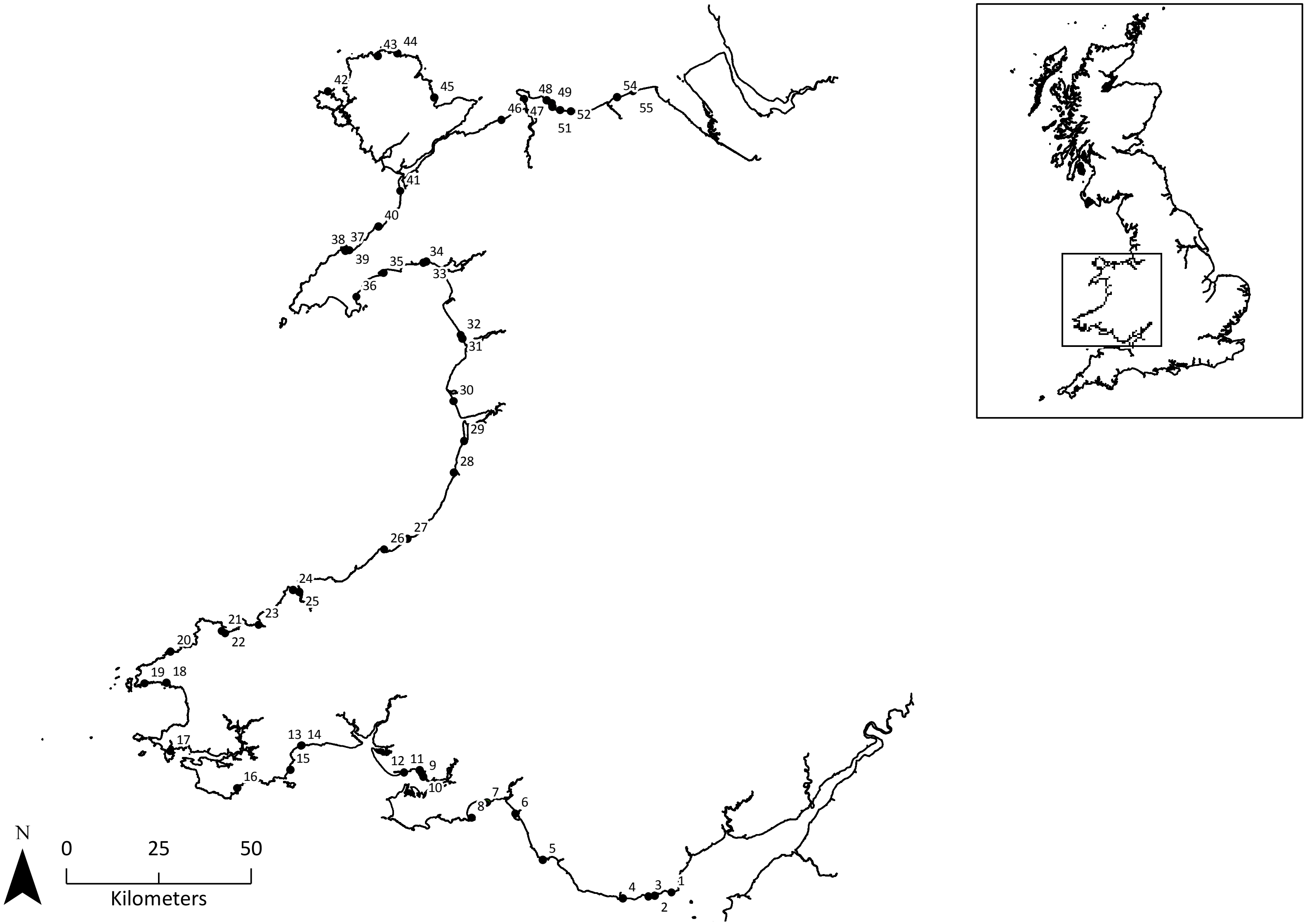

Figure 2.1 Fifty-five locations around the coast of Wales, UK, at which 125 intertidal coastal defence structures were surveyed (Table 2.1).

Table 2.1 One hundred and twenty five intertidal coastal defence structures surveyed at 55 locations (Figure 2.1) around the coast of Wales, UK.

#	Location	Structure	#	Location	Structure	#	Location	Structure
1	1-Swanbridge	Groyne	**43**	21-Goodwick	Groyne	**85**	38-Morfa Nefyn	Groyne
2	1-Swanbridge	Revetment	**44**	21-Goodwick	Revetment	**86**	39-Nefyn	Harbour wall
3	2-Barry E	Breakwater	**45**	21-Goodwick	Scour defence	**87**	40-Trefor	Groyne
4	3-Barry W	Harbour wall	**46**	22-Fishguard	Harbour wall	**88**	40-Trefor	Harbour wall
5	4-Aberthaw	Groyne1	**47**	22-Fishguard	Revetment	**89**	40-Trefor	Scour defence
6	4-Aberthaw	Groyne2	**48**	23-Parrog	Scour defence	**90**	41-Dinas Dinlle	Groyne1
7	5-Porthcawl	Harbour wall	**49**	24-Poppit Sands	Harbour wall	**91**	41-Dinas Dinlle	Groyne2
8	5-Porthcawl	Scour defence1	**50**	25-Gwbert	Groyne	**92**	42-Holyhead	Harbour wall
9	5-Porthcawl	Scour defence2	**51**	25-Gwbert	Revetment	**93**	42-Holyhead	Scour defence
10	5-Porthcawl	Seawall1	**52**	26-New Quay	Harbour wall1	**94**	43-Cemaes Bay	Harbour wall1
11	5-Porthcawl	Seawall2	**53**	26-New Quay	Harbour wall2	**95**	43-Cemaes Bay	Harbour wall2
12	6-Aberavon	Harbour wall	**54**	26-New Quay	Scour defence1	**96**	43-Cemaes Bay	Scour defence
13	6-Aberavon	Revetment	**55**	26-New Quay	Scour defence2	**97**	44-Porthllechog	Seawall
14	6-Aberavon	Scour defence1	**56**	27-Aberaeron	Groyne1	**98**	45-Benllech	Groyne1
15	6-Aberavon	Scour defence2	**57**	27-Aberaeron	Groyne2	**99**	45-Benllech	Groyne2
16	7-Swansea	Harbour wall	**58**	27-Aberaeron	Groyne3	**100**	46-Penmaenmawr	Groyne
17	7-Swansea	Scour defence	**59**	27-Aberaeron	Harbour wall	**101**	46-Penmaenmawr	Revetment
18	8-Mumbles	Revetment	**60**	28-Aberystwyth	Groyne	**102**	47-Llandudno W	Groyne1
19	8-Mumbles	Seawall1	**61**	28-Aberystwyth	Harbour wall	**103**	47-Llandudno W	Groyne2
20	8-Mumbles	Seawall2	**62**	28-Aberystwyth	Scour defence	**104**	47-Llandudno W	Scour defence
21	9-Llanelli E	Groyne	**63**	28-Aberystwyth	Seawall	**105**	48-Penrhyn Bay	Groyne
22	10-Llanelli W	Groyne	**64**	29-Borth	Breakwater	**106**	48-Penrhyn Bay	Revetment
23	11-Pwll	Revetment	**65**	29-Borth	Groyne1	**107**	49-Rhos on Sea	Breakwater
24	12-Burry Port	Breakwater	**66**	29-Borth	Groyne2	**108**	50-Colwyn Bay	Groyne1
25	12-Burry Port	Harbour wall	**67**	30-Tywyn	Breakwater	**109**	50-Colwyn Bay	Groyne2
26	13-Amroth	Groyne1	**68**	30-Tywyn	Groyne1	**110**	50-Colwyn Bay	Revetment
27	13-Amroth	Groyne2	**69**	30-Tywyn	Groyne2	**111**	50-Colwyn Bay	Seawall
28	13-Amroth	Groyne3	**70**	30-Tywyn	Groyne3	**112**	51-Old Colwyn Bay	Groyne1
29	13-Amroth	Groyne4	**71**	31-Barmouth	Groyne	**113**	51-Old Colwyn Bay	Groyne2

30	13-Amroth	Revetment	**72**	32-Llanaber	Revetment	**114**	51-Old Colwyn Bay	Revetment
31	14-Saundersfoot	Harbour wall	**73**	33-Criccieth E	Groyne1	**115**	51-Old Colwyn Bay	Seawall
32	15-Tenby	Harbour wall	**74**	33-Criccieth E	Groyne2	**116**	52-Penmaen Rhos	Groyne
33	15-Tenby	Revetment	**75**	33-Criccieth E	Harbour wall	**117**	52-Penmaen Rhos	Revetment1
34	15-Tenby	Seawall	**76**	34-Criccieth W	Groyne1	**118**	52-Penmaen Rhos	Revetment2
35	16-Stackpole Quay	Harbour wall	**77**	34-Criccieth W	Groyne2	**119**	53-Llanddulais	Groyne
36	17-Dale	Seawall	**78**	35-Pwllheli	Breakwater	**120**	53-Llanddulais	Groyne
37	18-Solva	Seawall	**79**	36-Abersoch	Groyne1	**121**	53-Llanddulais	Groyne
38	19-Porth Clais	Harbour wall	**80**	36-Abersoch	Groyne2	**122**	54-Rhyl	Groyne
39	19-Porth Clais	Scour defence	**81**	36-Abersoch	Harbour wall	**123**	54-Rhyl	Revetment
40	20-Porth Gain	Harbour wall	**82**	37-Porth Dinllaen	Breakwater	**124**	55-Prestatyn	Groyne1
41	20-Porth Gain	Seawall	**83**	37-Porth Dinllaen	Harbour wall	**125**	55-Prestatyn	Groyne2
42	21-Goodwick	Breakwater	**84**	37-Porth Dinllaen	Revetment			

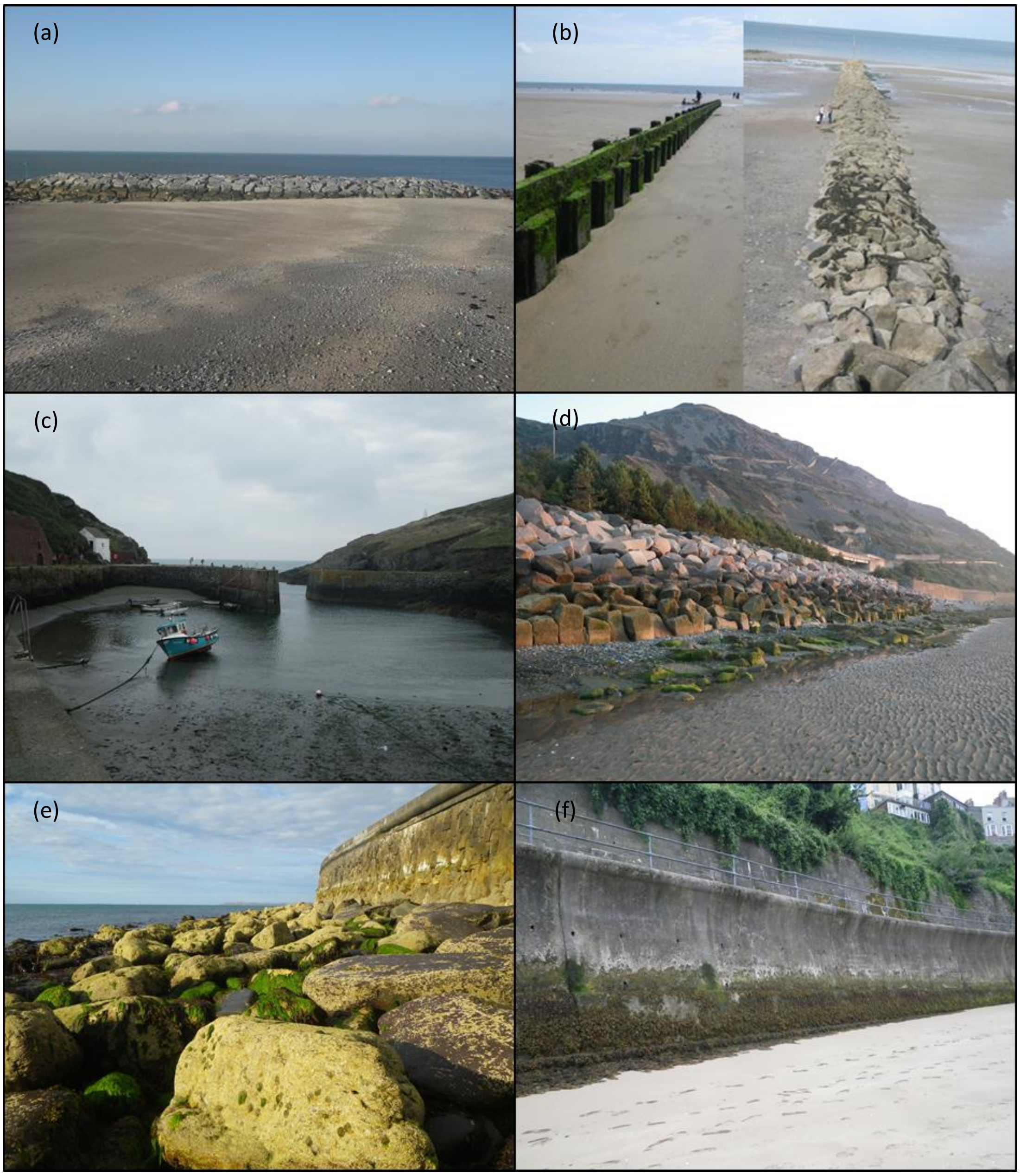

Figure 2.2 Examples of the six different types of intertidal coastal defence structures encountered around the coast of Wales, UK: (a) a breakwater; (b) two types of groyne; (c) a harbour wall; (d) a revetment; (e) scour defence; and (f) a seawall.

Table 2.2 Environmental and physical predictor variables recorded for 125 intertidal coastal defence structures surveyed around the coast of Wales, UK.
*Derived from Marine Nature Conservation Review (MNCR) site and littoral habitat descriptors (Hiscock 1996; Appendix I)
**See Appendix II

Variable	Category/Scale	Qualifiers/Notes
Wave exposure*	Very exposed	Prevailing wind and swell onshore
	Exposed	Prevailing wind onshore, offshore shallows/obstructions
	Moderately exposed	Prevailing wind offshore but onshore wind frequent
	Sheltered	Fetch <20 km; offshore shallows/obstructions
	Very sheltered	Fetch <20 km in any direction and <3 km to prevailing wind
Surrounding habitat*	Rocky Mixed Sandy Muddy	Characteristic surrounding habitat (<1 km) determined by cluster analysis** of multivariate % of Bedrock, Boulders (>256 mm), Cobbles (64-256 mm), Pebbles (16-64 mm), Gravel (4-16 mm), Sand (0.063-4 mm), Mud (<0.063 mm), Shells (empty), Artificial
Structure (functional descriptor)	Breakwater	Shore-parallel structures composed of consolidated units
	Groyne	Shore-perpendicular structures intended to stabilise beach materials
	Harbour wall	Shore-parallel solid walls with a leeward harbour
	Revetment	Consolidated units backing a shore
	Scour defence	Rubble or boulder scour protection at the foot of harbour walls
	Seawall	Solid walls backing a shore
Shape	Wall	Vertical or sloping solid barrier
	Riprap units	Large consolidated boulders (>512 mm)
	Fence	Vertical posts with horizontal panel barriers
	Dolos units	Interlocking pre-cast geometric units
	Rubble	Small boulders and cobbles (<512 mm)

Orientation	Shore-perpendicular Shore-parallel	
Aspect	Exposed Lee Both	In relation to the sea (shore-parallel structures) or to prevailing wind/swell (shore-perpendicular structures).
Lowest shore height*	Littoral fringe Eulittoral Sublittoral fringe	Estimated visually based on strand line and low tide mark
Surface relief*	1-5	Even-Rugged
Material	Concrete Granite Stone (other) Stone/concrete Wood	 E.g. locally-quarried sandstones and mudstones I.e. composite material
Surface inclination*	Vertical-Very steep Mixed Upper (>50%)	Characteristic surface inclination determined by cluster analysis** of multivariate % of Overhangs, Vertical faces (80-100°), Very steep faces (40-80°), Upper faces (0-40°) and Underboulders
Texture*	1-5	Smooth-Pitted
Microhabitat abundance*	1 = Low (≤6) 2 = Moderate (7-8) 3 = High (>8)	Sum of scores (1-5; none-many) assigned to Fissures (>10 mm), Crevices (<10 mm) and Rockpools
Microhabitat diversity*	0-6	Count of types of microhabitat present: Fissures (>10 mm), Crevices (<10 mm), Rockpools, Gully, Boulder holes, Quarry grooves

2.2.2 Data analysis

Statistical analyses were carried out in PRIMER v6 & PERMANOVA+ (PRIMER-E Ltd. Version 6, 2006).

2.2.2.1 Characterising the communities colonising artificial intertidal structures

Initially, four structures (i.e. #66 Borth groyne2, #86 Nefyn harbour wall, #91 Dinas Dinlle groyne2 and #115 Old Colwyn Bay seawall) were randomly selected and removed from the analyses in order to use them as test sites for subsequent validation of the predictive tool being developed. The remaining 121 structures were characterised in terms of their multivariate community compositions using hierarchical cluster analysis. The SACFORN data were first converted to numerical scores between 0 and 6 (i.e. S = 6, A = 5, C = 4, F = 3, O = 2, R = 1, Not recorded = 0). Clustering was undertaken based on the Bray-Curtis resemblance matrix of untransformed scores using the group average linkage approach. From the resulting dendrogram, four outliers (#9 Porthcawl scour defence2, #21 Llanelli East groyne, #76 Criccieth West groyne1 and #92 Holyhead harbour wall) were identified and removed from the set in order to allow effective modelling of linear relationships. Subsequent analyses were therefore based on 117 structures. Clusters of structures were then defined at three scales of detail in terms of their characteristic community types: 'Broad', 'Medium' and 'Fine'. Three scales of clustering were used in order to explore the level of detail in community composition that may be discriminated by the predictive tool being developed. The distinction of cluster groupings was performed through visual inspection of the dendrogram (i.e. identifying natural clustering of structures) and therefore entailed a degree of subjectivity. 'Broad' scale groupings were identified as clusters with relatively low percentage similarity, i.e. communities were only 'broadly' similar within these clusters, but cluster groups were distinguishable by coarse differences in community composition. 'Medium' and 'Fine' scale groupings were identified as clusters with progressively higher similarity, meaning that the characteristic species and their relative abundances were more consistent within cluster groups, and that the differences between cluster groups were more specific. We did not define *a priori* how similar different cluster groups should be at 'Broad', 'Medium' and 'Fine' scales, but reported the similarity within groups *post hoc*. In order to characterise the communities in each cluster group (at each of the three scales of detail), the mean richness of communities within clusters was calculated and SIMPER (similarity percentages) analysis (Clarke 1993) was used to identify the species (and their averaged relative abundances) contributing to the similarity of those communities.

2.2.2.2 Modelling the relationship between predictor variables and community response

Multivariate multiple regression using the DistLM (distance-based linear models) routine (Legendre and Andersson 1999, McArdle and Anderson 2001) was used to model the relationship between the 13 predictor variables (Table 2.2) and the multivariate community data recorded for each structure. Ordinal predictor variables were checked for multi-collinearity prior to analyses to avoid including redundant variables; no relationships were found to be strongly co-linear (Pearson's $|r| \leq 0.5$ in each case). Categorical predictor variables were expanded into sets of binary variables, taking a value of '1' for samples where that category occurred, and '0' elsewhere. The Step-wise selection procedure (Anderson et al. 2008), with AIC criterion (Akaike 1973), was employed to build the best parsimonious model of predictor variables for explaining the variation in the community data cloud, as described by Bray-Curtis resemblances between structures. For these analyses, individual hypotheses were tested against the adjusted significance level of $P = 0.01$ to reduce the potential for Type I errors as a result of multiple testing.

2.2.2.3 Using predictor variables to discriminate among community types

Discriminant analysis using the CAP (canonical analysis of principal coordinates) routine (Anderson and Robinson 2003, Anderson and Willis 2003) was used to identify axes through the environmental and physical data cloud (i.e. five predictor variables identified by the DistLM procedure) that were best at discriminating among community types (i.e. groups of communities defined by preliminary cluster analysis at 'Broad', 'Medium' and 'Fine' scales of detail). Structures were assigned to their respective 'Broad', 'Medium' and 'Fine' scale community types by coding with factors. The number of PCO (principle coordinate) axes was defined *a priori* as $m = 5$ in order to force inclusion of the full model set of predictor variables identified by the DistLM procedure. Analyses were based on the Euclidean resemblance matrix of the selected predictor variable values for each structure (n = 117), coded with integers on a mixture of ordinal and nominal scales (Table 2.3). Vector overlays corresponding to Spearman rank correlations were used to visualise the strength and direction of relationships between each predictor variable and the resulting CAP axes. Although discriminant analysis for group allocation can accommodate data on a mixture of scales, the nominal values coded to levels of Shape (Table 2.3) did not permit directional interpretation of correlation vectors for this variable.

Table 2.3 Five predictor variables included in CAP analysis, coded with integers.

*Considered ordinal on account of predominant particle sizes

Predictor variable	Scale for CAP analysis	Scale type
Lowest shore height	1 = Eulittoral fringe 2 = Eulittoral 3 = Sublittoral fringe	Ordinal
Surrounding habitat	1 = Muddy 2 = Sandy 3 = Mixed 4 = Rocky	Ordinal*
Shape	1 = Wall 2 = Riprap 3 = Fence 4 = Dolos 5 = Rubble	Nominal
Wave exposure	1 = Very sheltered 2 = Sheltered 3 = Moderately exposed 4 = Exposed 5 = Very exposed	Ordinal
Microhabitat abundance	1 = Low 2 = Moderate 3 = High	Ordinal

2.2.2.4 Validation of the model as a predictive tool

The 'leave-one-out' procedure (Lachenbruch and Mickey 1968, Seber 1984) was used to estimate allocation success (and misclassification error) of structures already in the model to the correct coded community types. In order to further test the predictive capability of the model, the CAP routine was run again with inclusion of the four test structures that were removed at the beginning of the analyses (i.e. #66

Borth groyne2, #86 Nefyn harbour wall, #91 Dinas Dinlle groyne2 and #115 Old Colwyn Bay seawall). Based on their known values for the combination of predictor variables identified by DistLM (Table 2.3), these four sites were allocated group membership to a predicted community type as defined by preliminary cluster analysis (at each of the 'Broad', 'Medium' and 'Fine' scales of detail in community composition). Group allocations were validated using unrestrained non-metric MDS (multi-dimensional scaling) plots of Bray-Curtis resemblances between untransformed community data for 121 structures (i.e. including test sites but not including outliers). Unrestrained plots were used to assess the appropriateness of predictions since they are based on variation across the data cloud as a whole, thus avoiding over-emphasis of the importance of the hypotheses underpinning constrained CAP plots (Anderson and Willis 2003).

2.3 Results

2.3.1 Characterising the communities colonising artificial intertidal structures

In total, 113 different taxa were observed colonising the 125 intertidal coastal defence structures surveyed around the coast of Wales, UK (Appendix III). Cluster analysis of 121 of these structures (i.e. not including the four test structures) identified four outliers in terms of their multivariate community compositions: #9 Porthcawl scour defence2, #21 Llanelli East groyne, #76 Criccieth West groyne1 and #92 Holyhead harbour wall (Figures 2.3-2.5). The remaining 117 structures were visually divided into four separate groups at the 'Broad' scale of clustering detail (~ 45-50% similarity; Figure 2.3), seven groups at the 'Medium' scale (~ 47-58% similarity; Figure 2.4) and ten groups at the 'Fine' scale (~ 47-68% similarity; Figure 2.5). The communities characterising each cluster group are described in Table 2.4 (see Appendix III for full SIMPER results).

The four 'Broad' scale community types were characterised, to some extent, by different levels of species richness: 'species-poor' Group A, 'moderately species-rich' Group C and 'species-rich' Groups B and D (Table 2.4). The two 'species-rich' groups were distinguishable on account of a higher dominance of brown canopy algae in Group B and the presence of lower-shore taxa, such as kelps, in Group D.

Some of the 'Medium' and 'Fine' scale community types identified within these 'Broad' groups were also distinguishable on account of their species richness. For example, at the 'Medium' scale Group D was divided into 'very species-rich' Group D1 (with numerous red algae and kelp species) and 'moderately species-rich' Group D2 (with fewer red algae and no kelps) (Table 2.4). Other groups, however, were separated and characterised by more subtle differences in the identities and relative abundances of composite taxa. For example, at the 'Fine' scale Group D1 was further divided into D1.1 and D1.2, both 'very species-rich', but one was characterised by the presence of kelps (D1.2), and the other by slightly fewer algal species but relatively high abundances of *Mytilus edulis* and *Sabellaria alveolata* (Table 2.4). Group A remained constant at all scales of clustering on account of high dissimilarity to other communities (< 40% similarity).

Closer inspection of the four outlying structures and the communities colonising them revealed conspicuous anomalies in each case that may explain their distinctness. The #9 Porthcawl scour defence2 supported a sparse community with no canopy algae, perhaps on account of the size and instability of rubble boulders. The #21 Llanelli East groyne supported unusually high abundances of fish, crabs and shrimp in 'rock pools' that had formed between riprap units. The #76 Criccieth West groyne1 supported only *Ulva* spp., perhaps on account of a recent disturbance event (the structure was partially-buried by sand at the time of survey). Finally, the #92 Holyhead harbour wall was colonised by very abundant barnacles and limpets on the exposed side, and mainly brown canopy algae on the lee side, but the lee side only supported lower-shore species, possibly because of a shallow substrate inclination and reduced tidal range inside the harbour.

Table 2.4 Characteristic communities colonising 121 intertidal coastal defence structures surveyed around Wales, UK, as described by SIMPER analysis of within-group similarities (Appendix III).

Cluster group: Visually defined from dendrogram of hierarchical cluster analysis with average group linkage at 'Broad' (Figure 2.3), 'Medium' (Figure 2.4) and 'Fine' (Figure 2.5) scales of detail; SR: Species richness; SACFOR scale relative abundances shown in brackets: S = Super Abundant, A = Abundant, C = Common, F = Frequent, O = Occasional, R = Rare (Appendix I)

Scale of detail	Cluster group	Structures	Average similarity	Community characteristics
Broad	A	6, 50, 63	51.1	Species-poor (mean SR = 7.7 ± 0.3 SE); dominated by *Ulva* spp. (C-A), with *Fucus spiralis*, *Pelvetia canaliculata*, *Porphyra* spp., *Chthamalus* spp. and *Littorina saxatilis* (all O-F).
	B	3, 18, 22-23, 33, 36-38, 41-42, 46-48, 51-52, 78, 94-95, 97-98, 102, 105, 107	55.6	Species-rich (mean SR = 25.1 ± 1.7 SE); dominated by several brown canopy algae spp., *Ulva* spp. and barnacle spp. (all F-A), with several gastropod spp. (O-F), mobile crustacean spp. (R-F), red algae spp. and other sessile fauna spp. (all R-O).
	C	1-2, 4-5, 8, 10-13, 15, 19-20, 24-32, 34, 43-44, 53, 56, 58, 65, 68-72, 75, 77, 79-81, 84-85, 89-90, 99-101, 103-104, 106, 108-111, 113-114, 116-125	56.0	Moderately species-rich (mean SR = 15.7 ± 0.6 SE); dominated by *F. spiralis*, *Ulva* spp. and barnacle spp. (all F-C), with several gastropod spp. (R-F) and red algae spp. (R), and few mobile crustacean spp. (R-F).
	D	7, 14, 16-17, 35, 39-40, 45, 49, 54-55, 57, 59-62, 64, 67, 73-74, 82-83, 87-88, 93, 96, 112	49.2	Species-rich (mean SR = 29.5 ± 2.1 SE); dominated by *Semibalanus balanoides*, *Ulva* spp. and *Patella vulgata* (all C-A), with numerous red algae spp. (R-F) and other sessile fauna spp. (R-O), several brown canopy algae spp. (O-F), including kelp spp. (R), several other gastropod spp. (R-F) and few mobile crustacean spp. (R-O).
Medium	A	As above	51.1	As above
	B	As above	55.6	As above
	C1	8, 11, 56, 58, 89, 104, 125	51.6	Moderately species-poor (mean SR = 13.6 ± 0.7 SE); dominated by *Ulva* spp. (C-A), with barnacle spp., several brown canopy algae spp. and *P. vulgata* (all R-F), several other gastropod spp. (R-O), and few red algae spp. and other sessile fauna spp. (all R).

	C2	1-2, 4-5, 10, 12, 19-20, 25, 34, 43-44, 75, 80-81, 84-85, 99, 103, 106, 110-111, 113-114, 118, 120, 123	62.4	Moderately species-poor (mean SR= 14.2 ± 0.7 SE); dominated by *F. spiralis*, *Ulva* spp. (both C-A) and barnacle spp. (O-C), with several gastropod spp. (R-F), and few mobile crustacean spp. (R-F) and red algae spp. (R-O).
	C3	13, 15, 24, 26-32, 53, 65, 68-72, 77, 79, 90, 100-101, 108-109, 116-117, 119, 121-122, 124	62.1	Moderately species-rich (mean SR = 17.6 ± 0.9 SE); dominated by barnacle spp., *Ulva* spp. and *F. spiralis* (all F-A), with several gastropod spp. (O-C), and few mobile crustacean spp., red algae spp. and other sessile fauna spp. (R-O).
	D1	7, 14, 35, 40, 49, 54-55, 64, 67, 82-83, 87-88, 93	54.4	Very species-rich (mean SR = 38.0 ± 2.0 SE); dominated by barnacle spp. and *P. vulgata* (all C-A), with *Ulva* spp., numerous red algae spp. and other sessile fauna spp. (all R-F), several brown canopy algae spp. (all O-C), including kelp spp. (R-O), several other gastropod spp. (R-C) and few mobile crustacean spp. (R-O).
	D2	16-17, 39, 45, 57, 59-62, 73-74, 96, 112	52.3	Moderately species-rich (mean SR = 20.4 ± 1.3 SE); dominated by *Ulva* spp. and *S. balanoides* (both C-A), with several brown canopy algae spp., gastropod spp. (all R-F), red algae spp. and other sessile fauna spp. (all R-O), and few mobile crustacean spp. (R-O).
Fine	A	As above	51.1	As above
	B1	3, 18, 22-23, 33, 36, 42, 46, 52, 78, 95, 98, 102, 105, 107	61.1	Species-rich (mean SR = 29.1 ± 1.7 SE); dominated by *F. spiralis*, *Ascophyllum nodosum* and barnacle spp. (all C-A), with *Ulva* spp., and several other brown canopy algae spp. (all O-F), gastropod spp., mobile crustacean spp. (all R-C), red algae spp. and other sessile fauna spp. (all R-F)
	B2	37-38, 41, 47-48, 51, 94, 97	57.3	Moderately species-rich (mean SR = 17.5 ± 1.3 SE); dominated by *A. nodosum*, *F. spiralis*, *P. canaliculata* and *Catenella caespitosa* (all C-S), with *Ulva* spp., other brown canopy algae spp. (all R-C), several gastropod spp. (R), and few mobile crustacean spp. and other red algae spp. (all R-F)
	C1.1	8, 11, 104, 125	58.8	Moderately species-poor (mean SR = 12.5 ± 0.9 SE); dominated by barnacle spp. and *Ulva* spp. (all C-S), with few gastropod spp., brown canopy algae spp. and other sessile fauna spp. (all R-F)

C1.2	56, 58, 89	71.6	Moderately species-poor (mean SR = 15.0 ± 0.6 SE); dominated by *Ulva* spp. and *Phorcus lineatus* (both C-A), with few brown canopy algae spp., barnacle spp. and other gastropod spp. (all O-F)
C2	As above	62.4	As above
C3	As above	62.1	As above
D1.1	7, 14, 54-55, 64, 67	60.4	Very species-rich (mean SR = 35.7 ± 2.5 SE); dominated by barnacle spp. and *Ulva* spp. (all C-A), with numerous gastropod spp. (R-C), several brown canopy algae spp. (R-F), red algae spp. and other sessile fauna spp. (all R-F), and few mobile crustacean spp. (R-O). *Sabellaria alveolata* and *Mytilus edulis* prominent (both F-C).
D1.2	35, 40, 49, 82-83, 87-88, 93	61.5	Very species-rich (mean SR = 39.8 ± 2.8 SE); dominated by barnacle spp., *P. vulgata* and Lithothamnia (all F-A), with *Ulva* spp., numerous brown canopy algae spp., including kelp spp., gastropod spp., other red algae spp. and other sessile fauna spp. (all R-C), and few mobile crustacean spp. (R-O).
D2	As above	52.3	As above

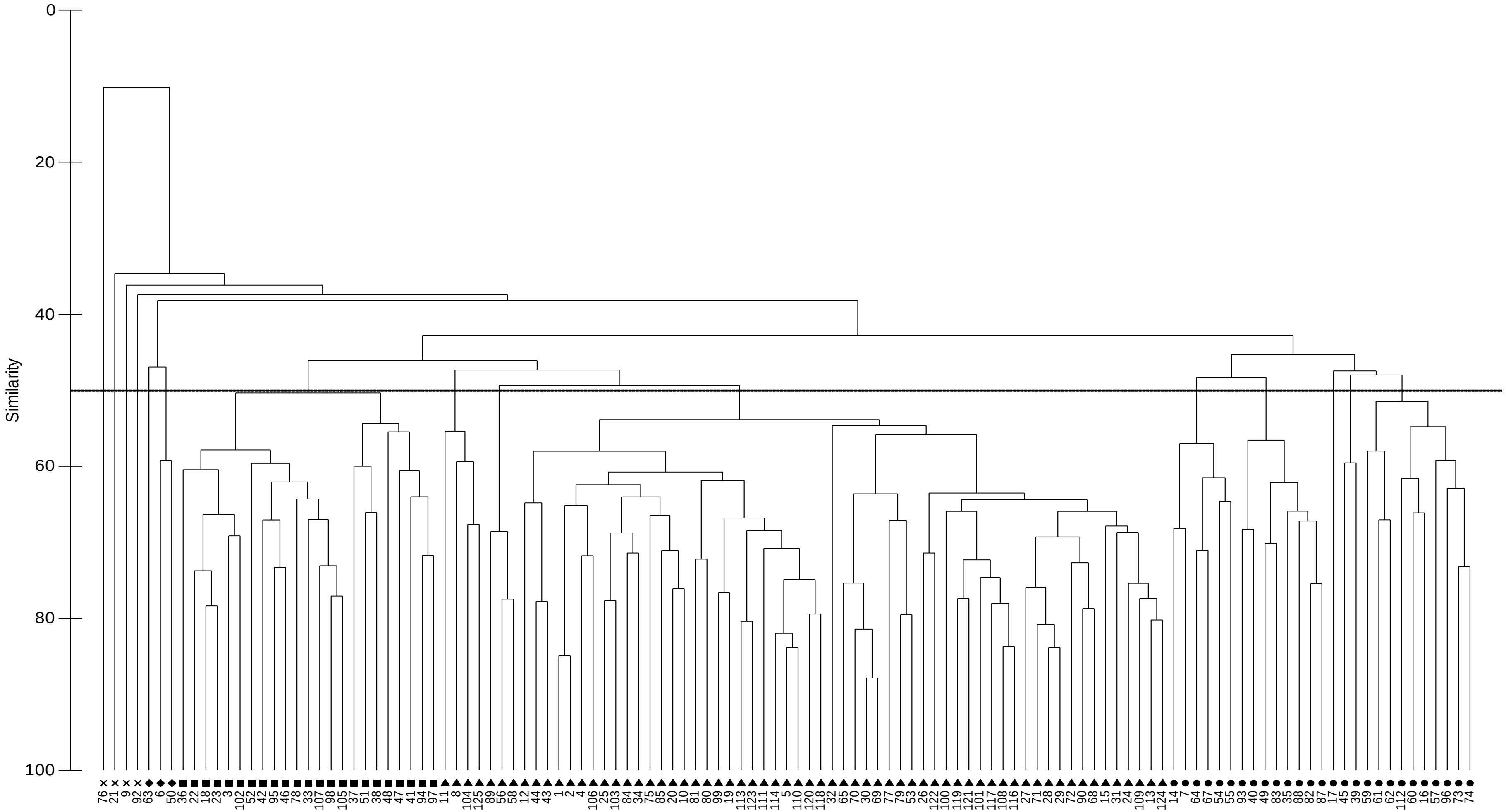

Figure 2.3 Intertidal coastal defence structures (n = 121) around the coast of Wales, UK, clustered by group average linkage of Bray-Curtis resemblances between multivariate community compositions. Symbology indicates ‘Broad’ cluster groups (~ 45-50% similarity) as described in Table 2.4: Group A (◆), Group B (■), Group C (▲), Group D (●) and four outliers (x).

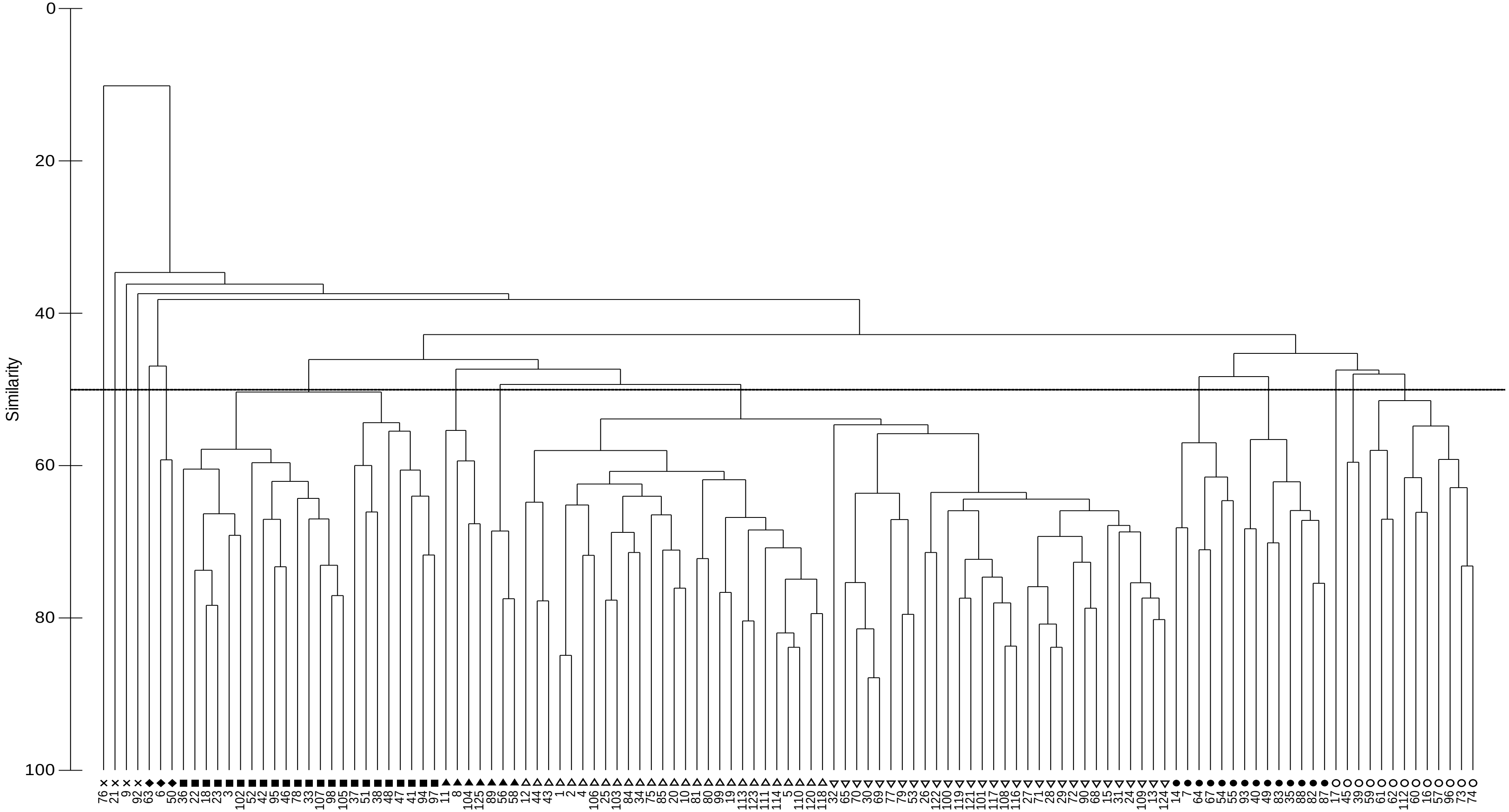

Figure 2.4 Intertidal coastal defence structures (n = 121) around the coast of Wales, UK, clustered by group average linkage of Bray-Curtis resemblances between multivariate community compositions. Symbology indicates 'Medium' cluster groups (~ 47-58% similarity) as described in Table 2.4: Group A (◆), Group B (■), Group C1 (▲), Group C2 (△), Group C3 (▽), Group D1 (●), Group D2 (○) and four outliers (x).

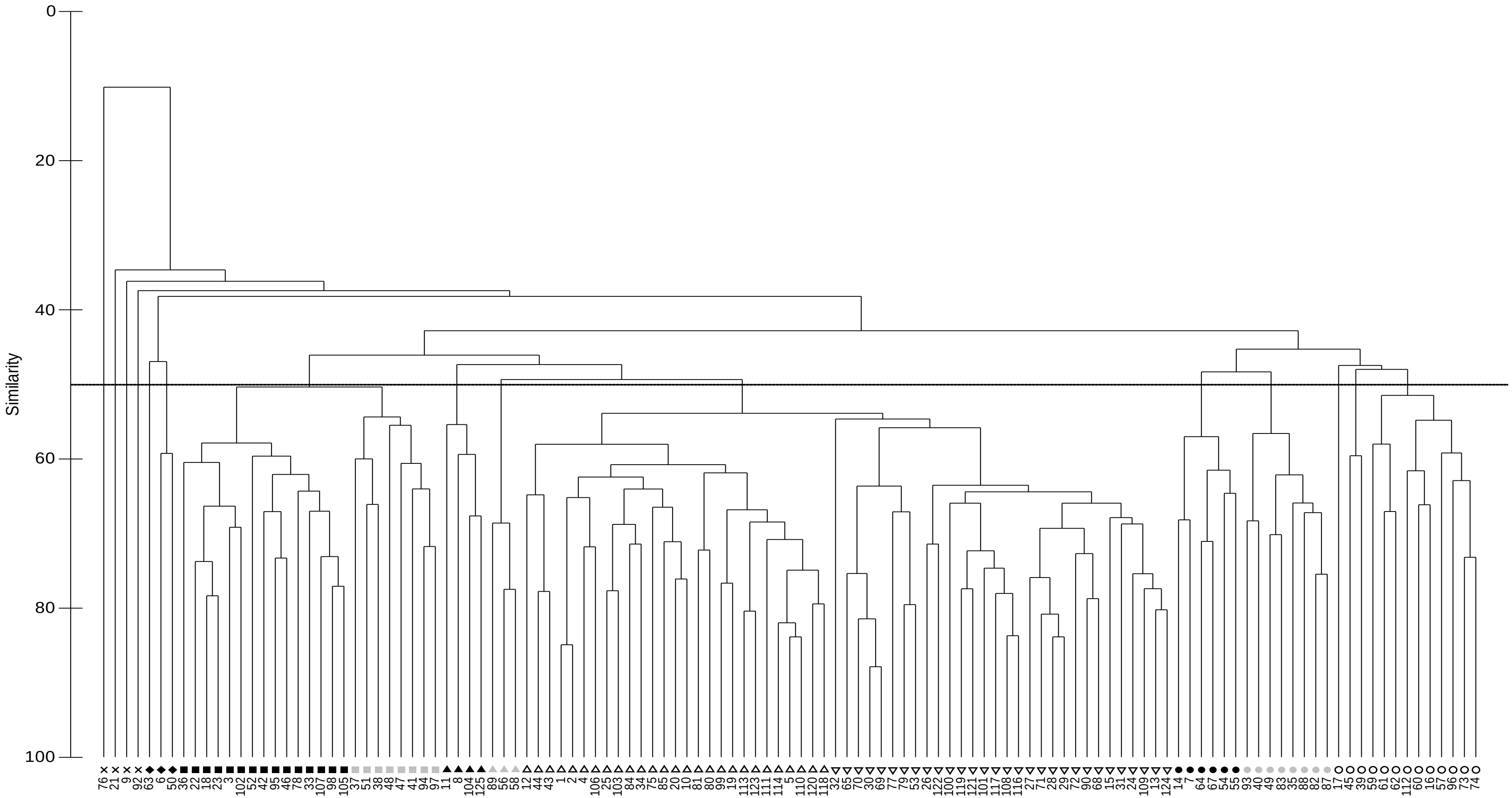

Figure 2.5 Intertidal coastal defence structures (n = 121) around the coast of Wales, UK, clustered by group average linkage of Bray-Curtis resemblances between multivariate community compositions. Symbology indicates ‘Fine’ cluster groups (~ 47-68% similarity) as described in Table 2.4: Group A (◆), Group B1 (■), Group B2 (■), Group C1.1 (▲), Group C1.2 (▲), Group C2 (Δ), Group C3 (∇), Group D1.1 (●), Group D1.2 (●), Group D2 (○) and four outliers (x).

2.3.2 Modelling the relationship between predictor variables and community response

DistLM indicated that eight out of the 13 recorded predictor variables (Table 2.2) independently explained a significant (*P* < 0.01) proportion of the variation in communities colonising structures (Table 2.5). The best parsimonious model solution included 'Lowest shore height', 'Surrounding habitat', 'Shape', 'Wave exposure' and 'Microhabitat abundance', which together explained 41.5% of the total variation in community composition (Table 2.5). The Step-wise selection procedure partitioned the proportional and cumulative contributions to explanatory power by each of the variables added step-wise to the model (Table 2.5).

Table 2.5 Marginal tests and parsimonious Step-wise solution (with AIC criterion) for DistLM linking environmental and physical predictor variables with multivariate communities colonising 117 intertidal coastal defence structures around Wales, UK.

Prop.: Proportion of variation explained; Cumul.: Cumulative variation explained

Marginal tests **Predictor variables**	**SS**	**Pseudo-F**	***P***	**Prop.**	**d.f.**
Lowest shore height	31215	13.292	**0.0001**	0.189	3
Structure	23376	3.662	**0.0001**	0.142	6
Surrounding habitat	18267	4.687	**0.0001**	0.111	4
Shape	15106	2.820	**0.0001**	0.092	5
Wave exposure	13493	2.492	**0.0001**	0.082	5
Material	12468	2.288	**0.0002**	0.076	5
Microhabitat abundance	11667	8.746	**0.0001**	0.071	2
Texture	9570	7.077	**0.0001**	0.058	2
Inclination	5212	1.858	0.0205	0.032	3
Aspect	4772	1.697	0.0391	0.029	3
Microhabitat diversity	3592	2.558	0.0103	0.022	2
Surface relief	3067	2.178	0.0234	0.019	2
Orientation	2558	1.81	0.0632	0.015	2

Step-wise solution **Model**	**AIC**	**Pseudo-F**	***P***	**Prop.**	**Cumul.**
+ Lowest shore height	829.96	13.292	**0.0001**	0.189	0.189
+ Surrounding habitat	820.33	5.289	**0.0001**	0.101	0.291
+ Shape	818.57	2.327	**0.0001**	0.057	0.347
+ Wave exposure	817.26	2.133	**0.0003**	0.050	0.397
+ Microhabitat abundance	815.84	3.027	**0.0005**	0.017	0.415

2.3.3 Using predictor variables to discriminate among community types

Discriminant analysis (using CAP) identified axes through the data cloud of the five DistLM-selected predictor variables (Table 2.5) that were best at discriminating among the different types of communities colonising structures (i.e. groups of communities defined by preliminary cluster analysis at ‘Broad’, ‘Medium’ and ‘Fine’ scales of detail; Table 2.4) (Figures 2.6-2.8). Vector overlays reflect the strength and direction of correlations between each axis and predictor variable (see Table 2.3 for directional interpretation of vectors).

At the ‘Broad’ scale definition of community types the first canonical axis explained the majority of the discriminatory power between types of communities (δ_1^2 = 0.568; Figure 2.6). Vector overlays indicate that ‘Lowest shore height’ was strongly correlated with this first axis (ρ = -0.910), as were, although to a lesser extent, ‘Microhabitat abundance’ (ρ = -0.600) and ‘Surrounding habitat’ (ρ = -0.346). Although there was some overlap between groups, structures assigned to the species-rich community Groups B (squares; Figure 2.6) and D (circles; Figure 2.6) were mostly plotted on the left-hand side in the canonical space, with species-poor Group A (diamonds; Figure 2.6) and moderately species-rich Group C (triangles; Figure 2.6) plotted towards the right. This suggests that species richness was higher on structures that had a lower ‘Lowest shore height’, higher ‘Microhabitat abundance’ and coarser ‘Surrounding habitat’ (although the correlation between ‘Surrounding habitat’ and this first axis was relatively weak). ‘Wave exposure’ (ρ = 0.897) and, to a lesser extent, ‘Shape’ (ρ = 0.384) were more correlated with the second CAP axis, which explained a much smaller proportion of the separation between groups (δ_2^2 = 0.179). Species-rich Group B (squares; Figure 2.6) was mostly plotted lower in the canonical space (associated with lower ‘Wave exposure’) than species-rich Group D (circles; Figure 2.6) and species-poor Group A (diamonds; Figure 2.6), indicating some discriminatory power between community types but no clear relationship between ‘Wave exposure’ and richness. Although the ‘Shape’ predictor was categorical in nature, and therefore could not be interpreted directionally, structures plotted lower in the canonical space were associated with the lower-numbered ‘Shape’ categories (1 = Wall, 2 = Riprap, 3 = Fence; Table 2.3), whilst those plotted higher were associated with the higher-numbered categories (4 = Dolos, 5 = Rubble) (although the correlation between ‘Shape’ and this second axis was relatively weak).

Similar relationships were illustrated for CAP axes discriminating among 'Medium' and 'Fine' scale community types (Figures 2.7 and 2.8, respectively). However, the influence of 'Surrounding habitat' was much stronger in these analyses, as shown by longer vectors strongly correlated with the second canonical axis in each case (ρ = -0.619 for 'Medium' scale groups; ρ = -0.832 for 'Fine' scale groups). The second axis in each of these analyses explained a greater degree of separation between groups than in the 'Broad' scale analysis (δ_2^2 = 0.276 for 'Medium' scale, δ_2^2 = 0.495 for 'Fine' scale). In particular, at the 'Medium' scale Group C2 (open triangles; Figure 2.7) was separated from Group C3 (open inverted triangles; Figure 2.7), and at the 'Fine' scale Groups B1 (black squares; Figure 2.8) and B2 (grey squares; Figure 2.8) and Groups D1.1 (black circles; Figure 2.8) and D1.2 (grey circles; Figure 2.8) were relatively separated. Again, despite some discrimination between different community groups along these second axes, there was no clear directional trend in terms of the characteristic species richness of communities (Table 2.4).

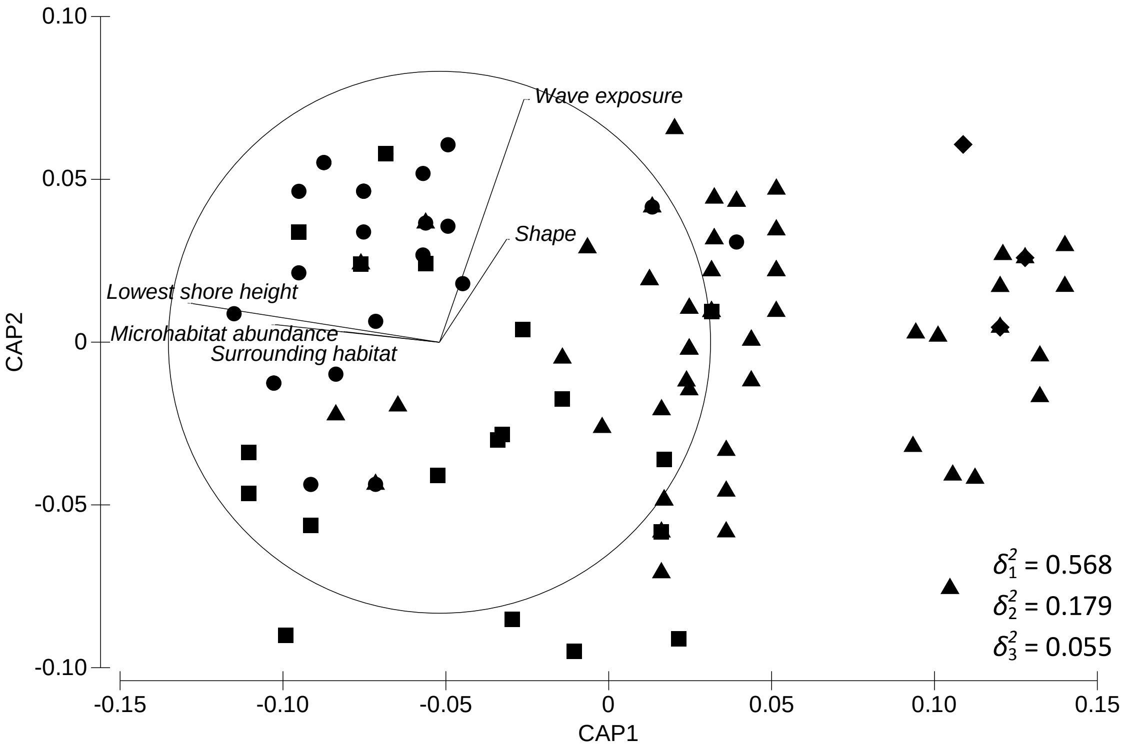

Figure 2.6 Canonical analysis of principle coordinates to discriminate among multivariate community types defined by 'Broad' scale hierarchical cluster analysis, based on five environmental and physical predictor variables: Lowest shore height, Surrounding habitat, Shape, Wave exposure and Microhabitat abundance. Symbology indicates cluster groups as described in Table 2.4: Group A (◆), Group B (■), Group C (▲) and Group D (●). Vectors: Spearman rank correlations of each predictor variable with the CAP axes; δ_i^2 : Eigenvalues for each canonical axis produced by the analysis.

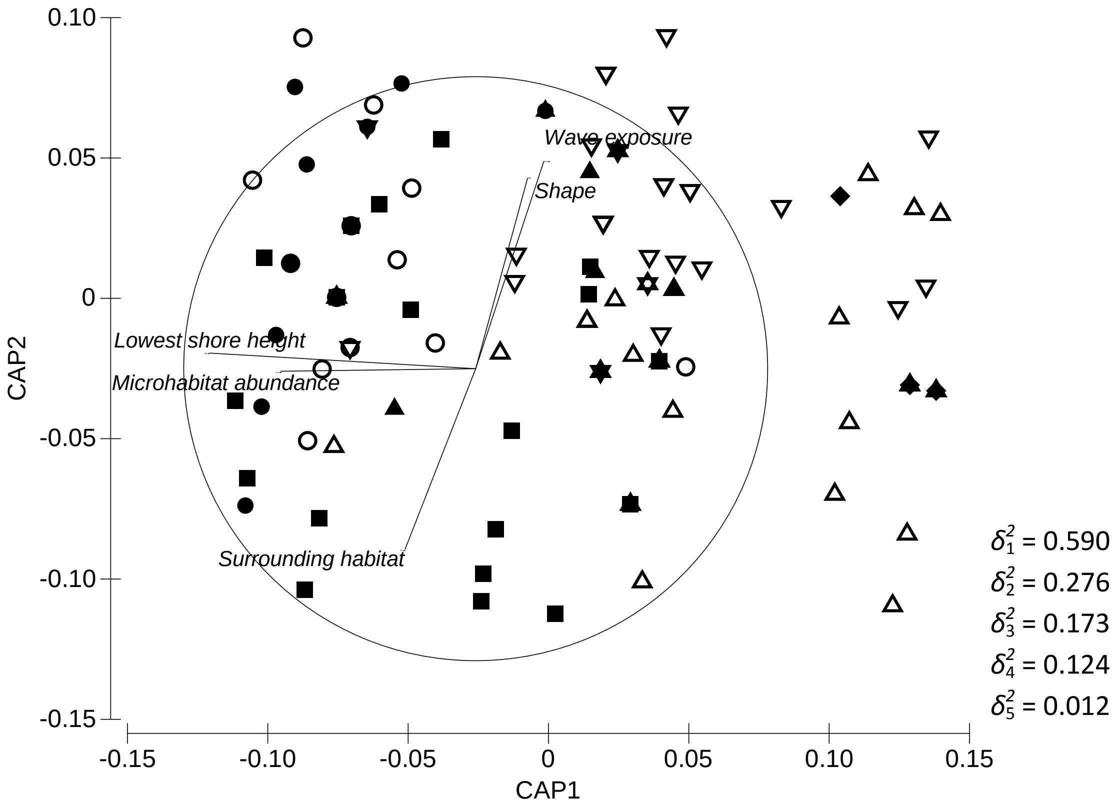

Figure 2.7 Canonical analysis of principle coordinates to discriminate among multivariate community types defined by 'Medium' scale hierarchical cluster analysis, based on five environmental and physical predictor variables: Lowest shore height, Surrounding habitat, Shape, Wave exposure and Microhabitat abundance. Symbology indicates cluster groups as described in Table 2.4: Group A (◆), Group B (■), Group C1 (▲), Group C2 (△), Group C3 (▽), Group D1 (●) and Group D2 (○). Vectors: Spearman rank correlations of each predictor variable with the CAP axes; δ_i^2 : Eigenvalues for each canonical axis produced by the analysis.

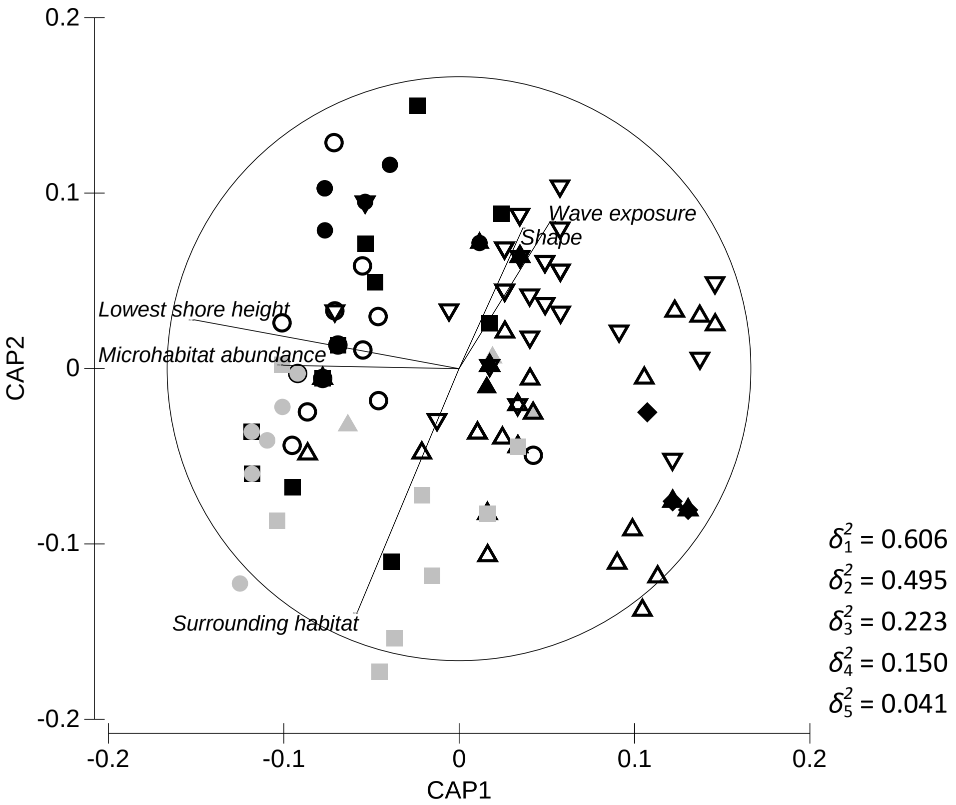

Figure 2.8 Canonical analysis of principle coordinates to discriminate among multivariate community types defined by 'Fine' scale hierarchical cluster analysis, based on five environmental and physical predictor variables: Lowest shore height, Surrounding habitat, Shape, Wave exposure and Microhabitat abundance. Symbology indicates cluster groups as described in Table 2.4: Group A (◆), Group B1 (■), Group B2 (■), Group C1.1 (▲), Group C1.2 (▲), Group C2 (△), Group C3 (▽), Group D1.1 (●), Group D1.2 (●) and Group D2 (○). Vectors: Spearman rank correlations of each predictor variable with the CAP axes; δ_i^2 : Eigenvalues for each canonical axis produced by the analysis.

2.3.4 Validation of the model as a predictive tool

The leave-one-out procedure estimated allocation success of structures in the model to the correct coded community types (Table 2.6). Allocation success was highest for community groups defined at the 'Broad' scale of detail (62.4%), particularly for Groups A (100%), C (64.1%) and D (74.1%) (Table 2.6; see also Table 2.4 for community group descriptions). Individual groups at the 'Medium' and 'Fine' scale of community definition also had high allocation success, but other groups had very low success (zero in some cases), leading to relatively low overall allocation success for these analyses (47.0% and 37.6%, respectively; Table 2.6).

Table 2.6 Cross-validation of CAP model by leave-one-out allocation of observations to groups defined at the 'Broad', 'Medium' and 'Fine' scale of detail in community composition (as described in Table 2.4).

Original group					**Classified**						**% correct**
'Broad' scale community groups											**62.4**
	A	B	C	D							
A	3	0	0	0							100
B	0	9	6	8							39.1
C	14	6	41	3							64.1
D	0	5	2	20							74.1
'Medium' scale community groups											**47.0**
	A	B	C1	C2	C3	D1	D2				
A	3	0	0	0	0	0	0				100
B	0	8	0	3	4	4	4				34.8
C1	0	0	1	2	3	0	1				14.3
C2	7	4	5	8	2	0	1				29.6
C3	3	2	2	3	19	1	0				63.3
D1	0	2	0	0	1	9	2				64.3
D2	0	2	0	1	0	3	7				53.85
'Fine' scale community groups											**37.6**
	A	B1	B2	C1.1	C1.2	C2	C3	D1.1	D1.2	D2	
A	3	0	0	0	0	0	0	0	0	0	100
B1	0	1	2	3	0	0	0	2	3	4	6.7
B2	0	0	4	0	1	1	0	0	2	0	50.0
C1.1	0	1	0	0	1	0	1	1	0	0	0
C1.2	0	0	0	1	0	1	0	0	0	1	0
C2	7	0	3	3	7	2	3	0	1	1	7.4
C3	2	1	1	7	1	0	17	1	0	0	56.7
D1.1	4	0	0	1	0	0	0	4	0	1	66.7
D1.2	0	0	0	0	0	0	0	0	7	1	87.5
D2	0	1	0	0	1	1	0	1	3	6	46.2

Table 2.7 Allocation of four test structures to group membership of predicted community composition as defined by 'Broad', 'Medium' and 'Fine' scale cluster analysis (Table 2.4). Group allocation was based on discrimination by CAP axes through the data cloud for five environmental and physical predictor variables: Lowest shore height, Surrounding habitat, Shape, Wave exposure and Microhabitat abundance (see Table 2.3 for variable scales; see Table 2.2 for notes and qualifiers).

#	Structure	Predictor variables					Predicted community group		
		Lowest shore height	Surrounding habitat	Shape	Wave exposure	Microhabitat abundance	'Broad'	'Medium'	'Fine'
66	Borth groyne2	2 (Eulittoral)	2 (Sandy)	3 (Fence)	5 (Very exposed)	3 (High)	C	C3	D1.1
86	Nefyn harbour wall	3 (Sublittoral fringe)	3 (Mixed)	1 (Wall)	2 (Sheltered)	1 (Low)	B	B	B2
91	Dinas Dinlle groyne2	2 (Eulittoral)	2 (Sandy)	2 (Riprap)	4 (Exposed)	1 (Low)	C	C3	C3
115	Old Colwyn Bay seawall	1 (Eulittoral fringe)	3 (Mixed)	1 (Wall)	4 (Exposed)	2 (Moderate)	A	A	A

In order to further test the predictive capability of the model, the CAP routine was run again with inclusion of the four test structures that were removed at the beginning of the analyses. Based on their known values for the five predictor variables included in the model, these four sites were allocated group membership to predicted 'Broad', 'Medium' and 'Fine scale community types (Table 2.7).

Unrestrained non-metric MDS plots of observed multivariate community data for 121 of the structures surveyed (i.e. including test sites but not including outliers) indicated varying degrees of appropriateness of predicted group memberships for the test sites (Figures 2.9-2.11). When structures were defined by 'Broad' (Figure 2.9) and 'Medium' (Figure 2.10) scale community types, the predicted group memberships assigned to each of the four test structures were appropriate according to their plotted positions in relation to other structures assigned to the same groups. At the 'Fine' scale of community definition there was more overlap between groups, and the predicted group membership for two of the test structures (#66 Borth groyne2 and #86 Nefyn harbour wall) appeared to be less appropriate (Figure 2.11). The Borth groyne (B) was assigned to 'Fine' scale community Group D1.1 (black circles; Figure 2.11) but was plotted closer to the group centroid of Group C3 (open inverted triangles; Figure 2.11), even though both groups had a relatively high level of allocation success during cross-validation of the CAP model (66.7% and 56.7%, respectively; Table 2.6). The Nefyn harbour wall (N) was assigned to 'Fine' scale community Group B2 (grey squares; Figure 2.11) but was plotted amongst structures assigned to Group B1 (black squares; Figure 2.11). In this case, Group B2 had a moderately high allocation success (50.0%; Table 2.6) but Group B1 had very poor success (6.7%; Table 2.6). In both cases, predicted community group allocations at the 'Broad' and 'Medium' scales appear to be more appropriate.

Structure #115 Old Colwyn Bay seawall (OCB), was assigned to community Group A at all three scales of clustering detail. Although its plotted position appears reasonable in relation to the other structures assigned to Group A (black diamonds; Figures 2.9-2.11), there was a degree of overlap with Group C at the 'Broad' scale (triangles; Figure 2.9), and Groups C2 (open triangles) and C3 (open inverted triangles) at both the 'Medium' (Figure 2.10) and 'Fine' (Figure 2.11) scales. Accordingly, these groups were frequently misclassified during cross-validation of the CAP model (e.g. 14 structures from Group C were misclassified to Group A in the ‘Broad’ scale analysis; Table 2.6). These classification errors may be explained by the separation of Group C (‘Broad’ scale) and Groups C2 and C3 (‘Medium’ and ‘Fine’ scale) into two distinct areas along the first canonical axis during discriminant analysis, overlapping with Group A on the right-hand side (Figures 2.6-2.8). Since this first axis in each case was correlated strongly with ‘Lowest shore height’ and ‘Microhabitat abundance’, these are likely to be the predictor variables causing misclassification of structures to Group A communities. For example, a structure with a ‘Lowest shore height’ value of ‘1’ (Eulittoral fringe) and a ‘Microhabitat abundance’ of ‘1’ (Low) would be likely to be allocated group membership to species-poor Group A (Table 2.4) but the colonising community may in fact be more similar to the moderately species-rich Group C.

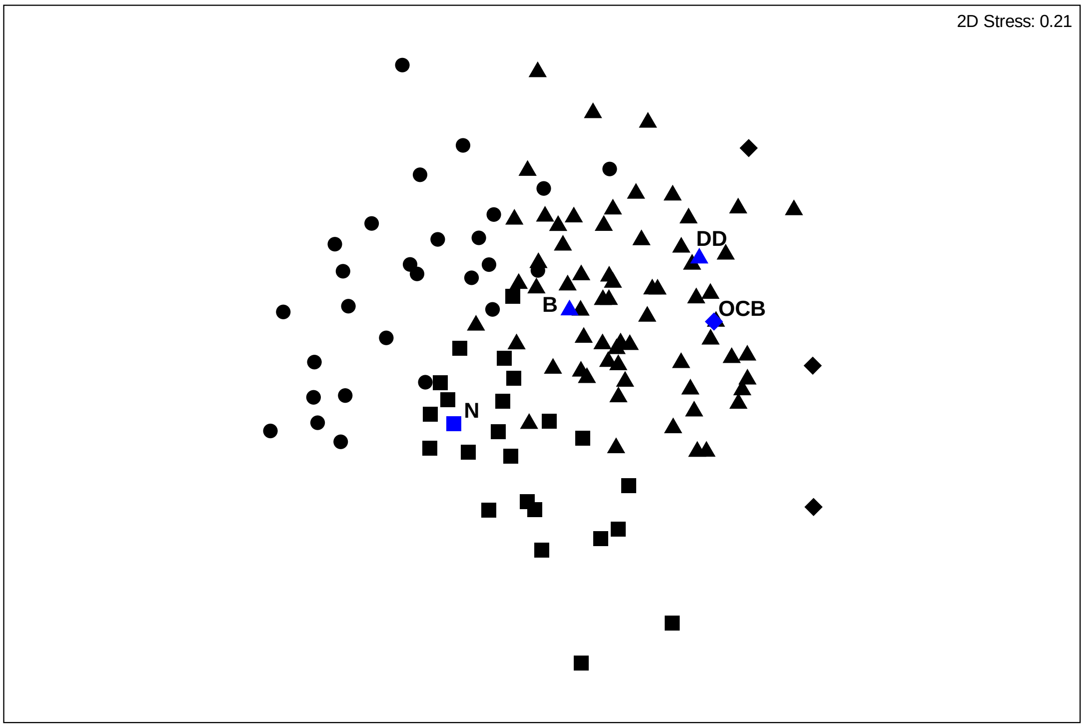

Figure 2.9 Non-metric MDS ordination of Bray-Curtis resemblances between multivariate community compositions for 121 intertidal coastal defence structures around the coast of Wales, UK. Symbology indicates ‘Broad’ scale cluster groups as described in Table 2.4: Group A (◆), Group B (■), Group C (▲) and Group D (●). Blue symbols indicate four test structures plotted according to their observed community compositions with symbology reflecting their predicted community group membership: B = #66 Borth groyne2 (predicted Group C), N = #86 Nefyn harbour wall (predicted Group B), DD = #91 Dinas Dinlle groyne2 (predicted Group C) and OCB = #115 Old Colwyn Bay seawall (predicted Group A).

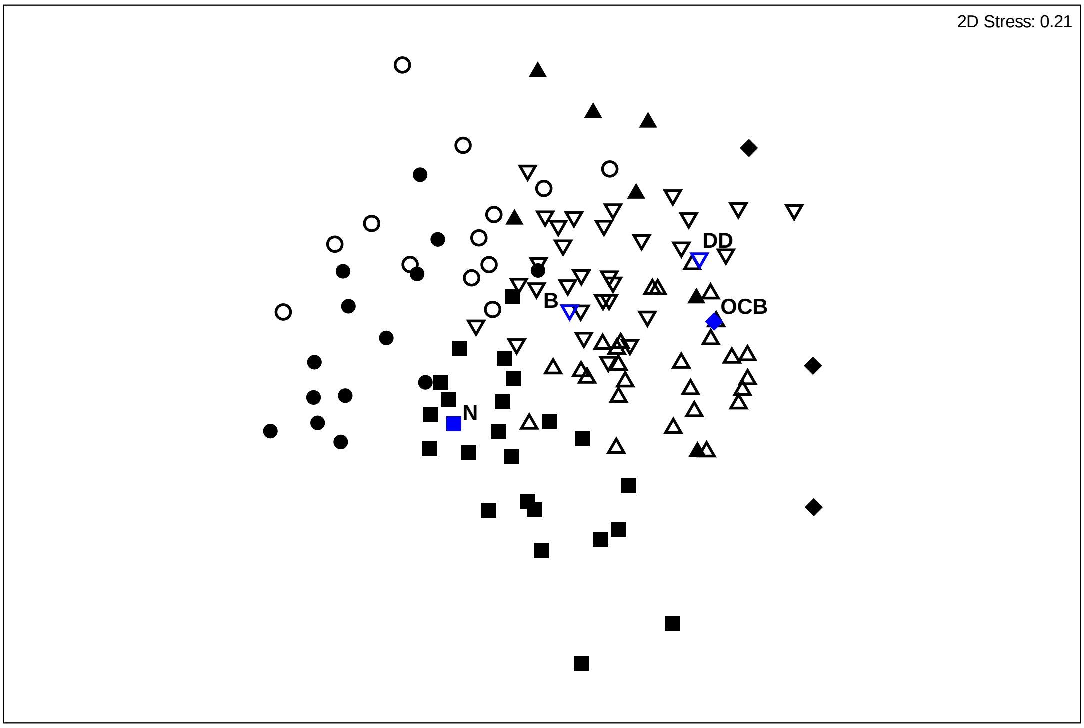

Figure 2.10 Non-metric MDS ordination of Bray-Curtis resemblances between multivariate community compositions for 121 intertidal coastal defence structures around the coast of Wales, UK. Symbology indicates 'Medium' scale cluster groups as described in Table 2.4: Group A (◆), Group B (■), Group C1 (▲), Group C2 (△), Group C3 (▽), Group D1 (●) and Group D2 (○). Blue symbols indicate four test structures plotted according to their observed community compositions with symbology reflecting their predicted community group membership: B = #66 Borth groyne2 (predicted Group C3), N = #86 Nefyn harbour wall (predicted Group B), DD = #91 Dinas Dinlle groyne2 (predicted Group C3) and OCB = #115 Old Colwyn Bay seawall (predicted Group A).

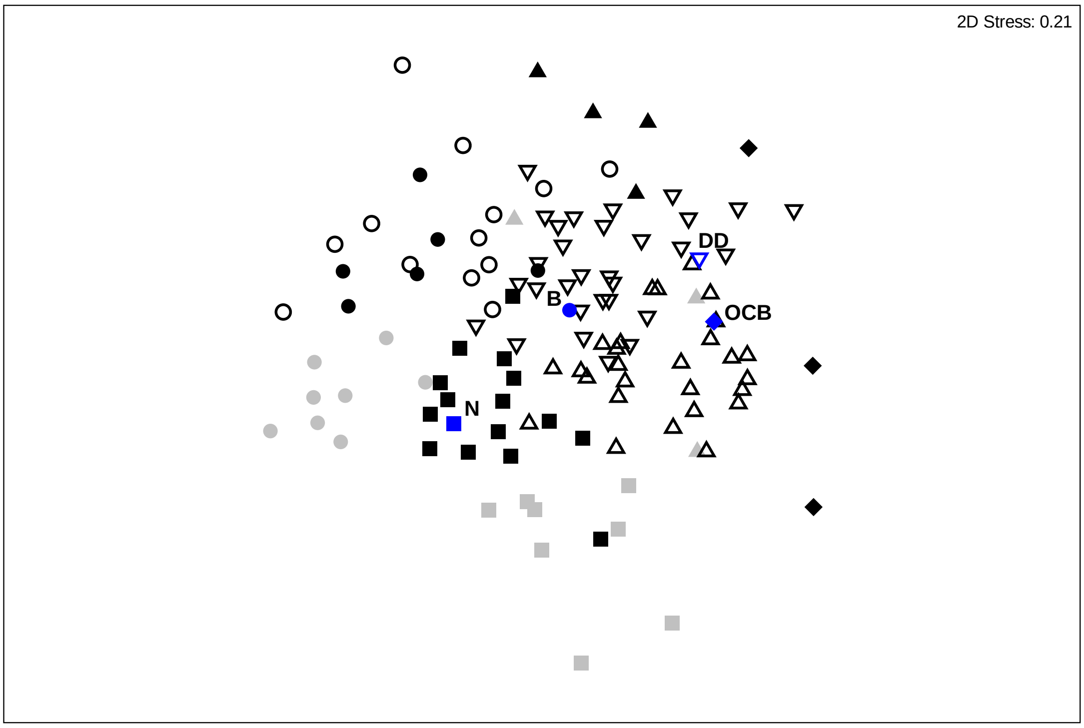

Figure 2.11 Non-metric MDS ordination of Bray-Curtis resemblances between multivariate community compositions for 121 intertidal coastal defence structures around the coast of Wales, UK. Symbology indicates 'Fine' scale cluster groups as described in Table 2.4: Group A (◆), Group B1 (■), Group B2 (■), Group C1.1 (▲), Group C1.2 (▲), Group C2 (△), Group C3 (▽), Group D1.1 (●), Group D1.2 (●) and Group D2 (○). Blue symbols indicate four test structures plotted according to their observed community compositions with symbology reflecting their predicted community group membership: B = #66 Borth groyne2 (predicted Group D1.1), N = #86 Nefyn harbour wall (predicted Group B2), DD = #91 Dinas Dinlle groyne2 (predicted Group C3) and OCB = #115 Old Colwyn Bay seawall (predicted Group A).

2.4 Discussion

2.4.1 Factors affecting community structure

The composition of communities recorded on the 125 intertidal coastal defence structures surveyed around Wales, UK, varied in species richness and in the identities and relative abundances of component taxa. Community development in intertidal habitats is often determined by a number of interacting physical, environmental and biological factors (Menge and Sutherland 1987, Benedetti-Cecchi 2000). The complexity of these interactions, together with high temporal and spatial variability in recruitment (Underwood and Fairweather 1989, Burrows et al. 2010), makes identification of the processes explaining species distributions difficult (e.g. Chapman 2003, Chapman and Bulleri 2003, Bulleri et al. 2005, Firth et al. 2014a, 2015b). In this study several physical design features and environmental parameters independently explained significant (although relatively low) proportions of variation in community structure. However, the best parsimonious model, explaining over 40% of the total variation, used just five of these variables: 'Lowest shore height', 'Surrounding habitat', 'Shape', 'Wave exposure' and 'Microhabitat abundance' (see Tables 2.2 and 2.3 for details). The modelled relationship between these five predictor variables and the multivariate community data was demonstrated to be an effective tool for predicting the characteristic communities that will colonise different types of coastal defence structures.

The 'Lowest shore height' of structures was the factor that independently explained the most variation in community composition. The vertical distribution of species on intertidal rocky shores is largely predictable by their tolerance to physical stressors (Foster 1971, Raffaelli and Hawkins 1996) and by competitive biological interactions (Hawkins and Hartnoll 1985, Menge and Sutherland 1987, Benedetti-Cecchi 2000). For example, kelp species such as *Laminaria digitata* only occur very low in the intertidal because of limited tolerance to desiccation and thermal stress (Dring and Brown 1982), whereas *Chthamalus* barnacles are outcompeted at lower shore heights but are tolerant to prolonged emersion on the high shore (Connell 1961). It is therefore unsurprising that structures positioned lower in the intertidal were colonised by different communities to those confined to the eulittoral fringe. However, the suitability of conditions for different species along the vertical shore gradient was clearly also influenced by other physical and environmental factors, either alleviating or exacerbating the stressors acting at different shore heights. More complex habitats can provide refuge from desiccation at higher shore levels (Raffaelli and Hughes 1978, Metaxas and Scheibling 1993, Moschella et al. 2005, Firth et al. 2013b), while disturbance from sand scour and wave action around the base of structures can create unfavourable conditions at low shore (Moschella et al. 2005). It follows, then, that 'Shape' and 'Microhabitat abundance' (reflecting different components of habitat complexity), and 'Surrounding habitat' and 'Wave exposure' (reflecting different components of local environmental conditions) were also included in the model selection.

The 'Shape' of structures in this study was described as either: Wall, Riprap units, Fence, Dolos units or Rubble. It is over-simplistic to suggest that one shape would always constitute a more complex habitat than another. Nevertheless, riprap and dolosse structures may have supported different taxa to vertical walls and fences on account of a greater variety in surface inclination (Connell 1999, Chapman and Underwood 2011, but see Firth et al. 2015b) and the influence of shading on colonising communities (Glasby 1999, Chapman and Blockley 2009, Marzinelli et al. 2011). At the smaller scale of habitat complexity, structures with high 'Microhabitat abundance' would likely have supported colonisation of more crevice- or pool-dwelling species than structures with few or no microhabitats. However, the importance of microhabitats would have been dependant on the physical harshness of conditions in each location (Wolcott 1973, Moran 1985). The 'Surrounding habitat' and 'Wave exposure' may have affected initial recruitment onto structures as well as habitat suitability post-settlement. Recruitment of species to coastal defences isolated from natural rocky shores (or other artificial rocky substrata) is dependent on long-distance dispersal capability of larvae and propagules. Therefore, species lacking such capability (e.g. some coralline algae or fauna lacking a planktonic phase; Dethier et al. 2003) may not have been able to colonise structures that were surrounded by soft-sediment habitat, or those that were sheltered from supply currents. In addition, disturbance from scour action and wave energy in exposed sandy environments (Moschella et al. 2005), and sedimentation in low-energy muddy environments (Airoldi 2003), may have reduced settlement and post-settlement survival of susceptible species on some structures. Conversely, filterfeeders such as mussels and barnacles are known to favour wave-exposed conditions (Lewis 1964, Moschella et al. 2005, Vaselli et al. 2008) and turf-forming or filamentous algae can become dominant in heavily-sedimented environments (Airoldi 2003, Vaselli et al. 2008).

Three other predictor variables ('Structure', 'Material' and 'Texture') also independently explained significant proportions of the variation in communities colonising structures, but were not included in the best parsimonious model. This may have been because of overlap with other variables in the model in terms of the portion of the variation explained. For example, much of the information contained in the variable 'Material' was already explained by the variable 'Shape', since the majority of Fences were wooden and the majority of Riprap units were granite. 'Shape', however, contained additional important information regarding the larger-scale complexity of habitats, not explained by the 'Material'. The omission of variables from the Step-wise model suggests that they were, in combination, less effective for explaining the total variation in communities.

Discriminant analysis provided further insight into the *portion* of the variation in communities explained by each of the five modelled predictor variables (i.e. how each variable was related to observed differences in communities). Several different community types were identified colonising structures, distinguishable on account of their characteristic species richness and the identities and relative abundances of component taxa. 'Lowest shore height' and 'Microhabitat abundance' were associated with elements of the model (i.e. the first canonical axis) that distinguished between communities largely on account of their species richness. Structures extending lower in the intertidal and with higher abundance of microhabitats were generally characterised by more species-rich communities than those confined to the upper shore and with few microhabitats. Although shore height has been shown to influence biodiversity on artificial intertidal structures previously (Pinn et al. 2005, Bulleri et al. 2005, Moschella et al. 2005, Borsje et al. 2011, Firth et al. 2013b), observed effects have not always been consistent or directional (Chapman 2003, Pinn et al. 2005, Firth et al. 2013b). Nevertheless, structures positioned (or extending) lower in the intertidal do tend to support a higher diversity of species than those confined to the upper shore (e.g. Moschella et al. 2005, Borsje et al. 2011, Firth et al. 2013b), probably because of the greater variety of niches they provide (even low-shore structures tend to be built upwards to include some upper-eulittoral habitat). Similarly, microhabitats such as pits, crevices and pools provide important refuge and variety in physical conditions (e.g. Raffaelli and Hughes 1978, Metaxas and Scheibling 1993), particularly in artificial habitats where they have been found to increase diversity by supporting species that would otherwise not be able to survive there (Chapman and Blockley 2009, Firth et al. 2013b, Browne and Chapman 2014, Aguilera et al. 2014, Evans et al. 2015, Perkol-Finkel and Sella 2015). Accordingly, Group A communities, associated with high-shore structures with low microhabitat abundance, comprised almost exclusively high-shore adapted species (i.e. *Fucus spiralis*, *Pelvetia canaliculata*: Hawkins and Hartnoll 1985; *Chthamalus* spp.: Connell 1961; and *Littorina saxatilis*: Connell 1972), whereas Groups B and D, associated with the opposite, contained numerous additional taxa, including several lower-shore and desiccation-sensitive species (e.g. kelps: Dring and Brown 1982; and certain encrusting fauna: Bulleri et al. 2002). However, although structures with high microhabitat abundance and low-shore positions tended to support similar (high) levels of species richness, the overlap of groups along this axis indicates that they were not always supporting the *same* species in the same relative abundances. Likewise, neither were those with low microhabitat abundance on the high shore.

The ‘Surrounding habitat’, ‘Wave exposure’ and ‘Shape’ predictors, although associated with less powerful elements of the model (i.e. the second canonical axis), discriminated between some of the community types that were not distinguishable by their species richness. For example, the ‘Broad’ scale community Groups B and D (both characteristically species-rich) were separated along this axis, partly on account of the identities of the dominant taxa. Communities in Group D, associated with higher wave exposure, were dominated by barnacles and limpets which are known to favour high-energy environments (Southward and Orton 1954, Moschella et al. 2005, Vaselli et al. 2008), while those in Group B were dominated by brown canopy algae, characteristic of communities in sheltered environments (Southward and Orton 1954, Jenkins et al. 1999, Jonsson et al. 2006). Similarly, ‘Fine’ scale community Group D1.1, with relatively high abundances of *M. edulis* mussels and the tube-building polychaete *S. alveolata*, was associated with higher wave exposure and more sedimentary habitats (i.e. characteristically sandy and muddy) than Group

D1.2. Again, mussels are known to favour wave-exposed environments (Lewis 1964, Moschella et al. 2005, Vaselli et al. 2008) and *S. alveolata* depends on a ready supply of suspended sand particles for tube-building (Wilson 1968, Firth et al. 2015a). The nominal nature of the 'Shape' variable made it difficult to interpret its influence on communities in the CAP model.

2.4.2 Predictive model as a management tool

Effective evaluation of different design options for coastal defence developments requires reliable prediction of the biological communities that will colonise different types of structures. The model developed in this study was demonstrated to be an effective tool for predicting the characteristic communities that will develop on intertidal structures around the coast of Wales, according to their 'Lowest shore height', 'Surrounding habitat', 'Shape', 'Wave exposure' and 'Microhabitat abundance'. Therefore, for a new development proposal, given the nature of the sediments and the wave exposure of the shore where a new structure is required, planners may forecast the communities that will develop in response to a variety of alternative design options for the structure's shape, position on the shore, and microhabitat availability. Although this five-parameter model solution explained only just over 40% of the total variation in communities colonising structures, leaving a considerable amount of variation unexplained, the CAP model was able to predict community group membership with up to 62% allocation success (for 'Broad' scale community groups). The success rate was reduced when attempting to predict finer detail in community characteristics, to 47% for 'Medium' scale groups and 38% for 'Fine' scale groups. Nevertheless, all scores were indicative of much greater predictive success than would be expected by chance alone (i.e. with four 'Broad' scale groups, seven 'Medium' scale groups and ten 'Fine' scale groups, the probability of allocation to each group under null hypotheses would be 25%, 14% and 10%, respectively).

The different types of communities colonising structures were characterised at three different scales of clustering in order to investigate the level of detail in community structure that could be discriminated by the predictive model being developed. The high allocation success for predicting 'Broad' scale communities entailed considerable compromise of detail about the identities and abundances of component taxa, although different levels of species richness were broadly predictable. The level of community detail required in a model would depend on the overall management objectives or mitigation requirements of a development. For example, if licence conditions specified that novel structures should support diverse intertidal communities, then a 'Broad' scale model may be adequate. If, however, developers wished (or were required) to provide habitat for specific target species, either to add value to the development or to mitigate losses elsewhere (e.g. Ambrose 1994, Spanier et al. 2010), then it may be necessary to use finer-scale community modelling, accepting a lower predictive confidence. Similarly, if developers were required to minimise the risk of invasion by non-native species, then finer-scale modelling would be necessary (although in this study, few non-native species were recorded colonising intertidal coastal defence structures around Wales; Appendix III; see also Chapter 5 for further discussion).

2.4.3 Possible improvement of the model

There is potential room-for-improvement in our model presented in this study. Some of the variation in communities could not be explained by the predictor variables modelled, despite distinct differences in richness and community structure. For example, the CAP axes did not discriminate between 'Medium' scale Groups D1 and D2, despite their different characteristic communities (i.e. structures with similar values for all five predictors were supporting two distinct community types). This could be a product of inherent stochastic recruitment patterns (Underwood and Fairweather 1989, Burrows et al. 2010), but alternatively may indicate the influence of some other factor (or factors) not included in the model. Additional parameters worth investigating, in light of their known capacity to affect intertidal colonisation, include: the age of structures (Connell and Glasby 1999, Pinn et al. 2005), including in the context of time since the last major disturbance event (e.g. from maintenance activities; Airoldi and Bulleri 2011); the total extent of the habitat (Hawkins and Hartnoll 1980); proximity to sources of pollution (Crowe et al. 2000, Archambault et al. 2001, Hewitt et al. 2005); and human use of structures or nearby areas (Crowe et al. 2000, Airoldi et al. 2005b). As well as incorporating additional parameters, it may be possible to improve the model performance by refining the definition of characteristic community clusters and predictor variables already in use. Some degree of subjectivity was necessary when identifying community groupings from the preliminary cluster analysis, and also when defining category levels of predictor variables (although most were based on widely-accepted MNCR definitions; Hiscock 1996).

The model was designed to be a straightforward tool for developers wishing to predict the type of community that will colonise a new intertidal structure. However, for those structures with both exposed/seaward and lee/landward aspects (i.e. in the Both category of the 'Aspect' variable), it is very likely that community development would differ markedly on the two different sides of the structure (Southward and Orton 1954, Moschella et al. 2005, Jonsson et al. 2006, Vaselli et al. 2008). The 'Wave exposure' variable included in the model reflected the morphology and aspect of the coastline, but did not differentiate between different sides of the same structure. The finer-scale influence of exposure *was* considered in the analysis to some extent, within the 'Orientation' and 'Aspect' variables, but they did not, alone or in-combination, explain significant proportions of the variation in communities. There is some suggestion that this whole-structure approach may have concealed meaningful ecological patterns acting at finer spatial scales, thus reducing the performance of the model. For example, the 'Fine' scale community Groups B1 and B2 were somewhat separated by the CAP axis correlated with 'Wave exposure'. Group B2, associated with lower exposure, was characterised by a dominance of brown canopy algae, consistent with communities in sheltered environments (Southward and Orton 1954, Jenkins et al. 1999, Jonsson et al. 2006). Group B1, associated with higher exposure, was characterised partly by a dominance of barnacles, consistent with communities in exposed environments (Moschella et al. 2005, Vaselli et al. 2008), but also by a dominance of brown canopy algae. The dominance of both barnacles *and* canopy algae may be indicative of shore-parallel structures on an exposed open coast, providing both exposed and sheltered habitats. Misclassification error for Group B1 was particularly high, perhaps because structures were assigned to high 'Wave exposure' categories at the broad spatial scale (leading to allocation to community groups characteristic of exposed environments). It would be interesting to investigate the potential of a similar model at the finer spatial resolution, predicting the communities that would develop on each side of structures separately, simplifying the 'Aspect' categories to Exposed or Lee only (i.e. not pooling them on structures with Both). This may improve the discriminatory power and reliability of the model, particularly when predicting finer-scale detail in community composition. It may, however, become somewhat convoluted as a management tool for application.

Although the model was tested and validated on four different structures from within the study area, the scope of its application is not yet known. It will be necessary to test the model more widely on structures in different locations around the UK (and further afield) in order to determine its potential as a tool for coastal management. It is anticipated that a different model would need to be developed based on the species pool in each biogeographical region, but it may be possible to generalise models by using functional, rather than taxonomic, groupings. Even within the survey region used in this study (i.e. the coast of Wales), meso-scale biogeographic patterns and processes, such as larval retention and sediment supply, are likely to be variable (Burrows et al. 2010). For example, recruitment may be higher in embayments such as Cardigan Bay and the Menai Strait (Herbert et al. 2007), and sediment/nutrient loads are likely to be elevated, whilst salinity decreases, towards the Bristol Channel and Liverpool Bay (e.g. Abdullah and Royle 1973, Collins 1987). Further, several southern species are known to reach their northerly range limit in Wales around the Llŷn Peninsula or Anglesey (Crisp and Knight-Jones 1955, Lewis 1964). These factors should be considered more closely in refinement of the model. Nevertheless, this first attempt to predict communities based on empirical observations demonstrated potential as an effective management tool for environmentally-sensitive design in coastal defence developments. Further, the broad statistical approach presented may prove of value for alternative applications in different systems.

2.4.4 Conclusions

In response to evolving marine planning policies (e.g. HM Government 2011), it is becoming increasingly necessary to incorporate ecologically-sensitive design into new coastal developments. On the basis of recent research into the ecology of artificial structures (e.g. Moschella et al. 2005, Burcharth et al. 2007, Firth et al. 2013b, 2014b), Firth et al. (2013a, 2014b, 2015b) recommended placing coastal defences low down in the intertidal and maximising microhabitat heterogeneity as a means of promoting biodiversity (on the structures themselves), which our findings support. However, the management objectives (or mitigation requirements) of new developments may necessitate more accurate prediction of the specific communities that will colonise different structures. To date, the complexity of interactive effects and high levels of natural variability have precluded this. In this study we have demonstrated the potential for statistical modelling (based on empirical field observations) to be used as a tool for predicting the ecological responses that are likely to result from different engineering design options.

We characterised the different types of biological communities that were colonising coastal defence structures around the coast of Wales, UK. We then modelled the relationship between these communities and a number of physical design features and environmental parameters that we anticipated may have some effect on the ecology of structures. The best parsimonious model for describing linear relationships included five variables: 'Lowest shore height', 'Surrounding habitat', 'Shape', 'Wave exposure' and 'Microhabitat abundance'. Our findings demonstrate the model to be an effective tool for predicting the characteristic communities that will develop on different types of structures in different locations. It further highlights the value of post-construction monitoring of colonising communities (which is rarely implemented following coastal defence developments) for improving our understanding of the ecological implications of future developments (discussed previously by Airoldi et al. 2005a). In light of the rapid proliferation of artificial structures in the marine environment, this predictive capability will be essential to mitigate ecological impacts and maximise the potential secondary benefits that can be built-in to engineered developments.

CHAPTER THREE

Drill-cored rock pools: an effective method of ecological enhancement on artificial coastal structures

Abstract

It is widely accepted that intertidal artificial structures (such as breakwaters, groynes and seawalls) are poor substitutes for natural rocky habitats, often supporting different and less diverse communities of marine life. Structures can, however, be enhanced through engineering interventions that introduce novel microhabitats, thereby increasing their topographic complexity. While several studies have tested interventions that incorporate novel water-retaining features into structures, there remains a need for additional trials to identify alternative cost-effective designs. We created artificial rock pools of two depths (12 cm, 5 cm) by drill-coring into a shore-parallel intertidal granite breakwater, to investigate their potential as an intervention for delivering ecological enhancement. The experiment was replicated in two different seasons (spring and autumn) to assess the importance of the timing of installation. We compared biodiversity (measured as species richness and community structure) and functioning (measured as gross primary productivity) in the drill-cored pools, on adjacent rock surfaces on the breakwater, and in natural pools on nearby rocky shores. Over a period of 30 months, the artificial pools supported greater species richness than adjacent granite rock surfaces, and similar richness and productivity to natural pools. Community composition was, however, different between artificial and natural pools. The depth and timing of installation of artificial pools did not affect richness or productivity, but both factors did affect the structure of communities colonising the pools. Although these novel habitats did not support the same communities as natural rock pools, they provided important habitat for several species that were otherwise absent at mid-shore height on the breakwater. These findings reveal the potential of drill-cored rock pools as an affordable and easily-replicated means of enhancing biodiversity on coastal defence structures, both at the design stage and retrospectively. Reasonable advice to practitioners would be that Beta diversity may be increased by installing artificial pools with a variety of different depths. Further, that installing artificial pools in spring and autumn will lead to similar ecological outcomes, although natural variability in larval and propagule recruitment may result in different communities.

3.1 Introduction

Intertidal coastal defence structures are typically colonised by organisms found on adjacent rocky shores (Southward and Orton 1954, Chapman 2003, Chapman and Bulleri 2003, Pinn et al. 2005, Moschella et al. 2005, Firth et al. 2015b), but they tend to support lower diversity (Chapman 2003, Pinn et al. 2005, Moschella et al. 2005, Pister 2009, Firth et al. 2013b, Aguilera et al. 2014) and different relative abundances of taxa (Chapman and Bulleri 2003, Knott et al. 2004, Pinn et al. 2005, Moschella et al. 2005). The diversity deficits reported on artificial coastal structures have been attributed to fewer mobile fauna (Chapman 2003, Pister 2009, Aguilera et al. 2014), lower-shore and other desiccation-sensitive taxa (Moschella et al. 2005, Firth et al. 2015b), and proportionally-rarer taxa (Chapman 2003). Coastal defences are often constructed in high-energy, erosive soft-sediment environments, where there tends to be greatest need for coastal protection. It has been suggested that high disturbance regimes caused by wave energy and sand scouring may be one reason for the lower epibiotic diversity recorded on structures (Moschella et al. 2005). Low biodiversity has also been linked to reduced topographic complexity when compared with natural rocky shores (Chapman 2003, Moschella et al. 2005, Aguilera et al. 2014, Firth et al. 2015b). For example, construction materials (e.g. quarried granite, concrete) often have smoother surface texture than rocky shore substrata, and structures tend to lack the diversity of microhabitats (e.g. pits, crevices, pools) characteristic of natural shores (Moschella et al. 2005, Aguilera et al. 2014).

Biodiversity on coastal defences can be enhanced through engineering interventions that introduce novel microhabitats to structures, thereby increasing their topographic complexity (Chapman and Underwood 2011, Firth et al. 2014b, Perkol-Finkel and Sella 2015). Rock pools provide refuge from fluctuations in temperature and desiccation stress, and can extend the vertical distribution of lower-shore species (see Metaxas and Scheibling 1993 for review). It has recently been demonstrated that rock pools support greater species diversity than emergent substrata in both natural (Firth et al. 2013b, 2014a) and artificial (Firth et al. 2013b) habitats, but they are relatively uncommon in artificial systems (e.g. Firth et al. 2013b, Aguilera et al. 2014). Water-retaining features mimicking rock pools have been added to vertical seawalls in Sydney Harbour, both during construction (i.e. shaded recesses wih water-retaining lips: Chapman and Blockley 2009) and retrospectively (i.e. concrete flower pots bracketed to walls: Browne and Chapman 2014). These engineered habitats were colonised by a variety of intertidal organisms and were found to be easy, cost-effective ways of enhancing the ecological condition of vertical seawalls. However, both designs had limitations; the shaded recesses may not provide suitable habitat for the full range of intertidal taxa since they are continually shaded; and several of the flower pots were lost from the walls within seven months of deployment (Browne and Chapman 2014). It is also unlikely that these novel habitats would perform in the same way on other types of artificial structures in other locations; Sydney Harbour is a semi-enclosed environment with a small tidal range, unlike the exposed open shorelines where coastal defence structures are frequently required. Habitat enhancement interventions intended for coastal defence schemes should be robust against disturbance from extreme weather events that are frequently experienced in exposed environments. Therefore, there remains a need for additional long-term, fully-replicated trials to determine the potential biodiversity benefits of incorporating different types of water-retaining features within coastal defence structures.

Here we investigate drill-cored artificial rock pools as a durable, affordable and replicable habitat enhancement intervention on an intertidal coastal defence breakwater. We evaluate their potential to increase biodiversity on the breakwater and to provide surrogate habitat for rocky shore communities, i.e. functionally-equivalent to natural rock pool habitat in terms of biodiversity and primary productivity. Primary productivity was considered an important metric since it provides unique information on the ecosystem services supported by rock pool communities (e.g. carbon sequestration, potential for trophic exchange) which may not be explained by species composition alone (Griffin et al. 2010). The cost of the rock pool intervention is directly related to the time taken to drill the artificial pools, which in turn is directly related to the depth of the pools created. Therefore, although the artificial pools were all designed to replicate small unshaded rock pools on nearby rocky shores, we trialled the design with two different depths (12 cm and 5 cm). Martins et al. (2007) suggested that deeper rock pools support more diverse and more productive communities than shallow ones because they provide more stable environmental conditions (but see Firth et al. 2014a). In natural systems, there is little distinction in the habitat provided by five and 12 cm deep rock pools, and previous studies consider all pools in this range to be shallow (e.g. Firth et al. 2014a). However, the artificial pools trialled in this study were cylindrical with vertical sides, so this magnitude of difference may be of greater consequence to habitat provision (e.g. if deeper pools were more shaded by the vertical sides: Glasby 1999, Chapman and Blockley 2009). Further, the effect of rock pool depth in artificial systems is not well understood (but see Browne and Chapman 2014), and ecological responses may be more pronounced (e.g. Firth et al. 2013b).

We compared biodiversity (measured as species richness and community structure) and functioning (measured as gross primary productivity) in the drill-cored artificial rock pools, and on adjacent granite rock surfaces on the breakwater, testing hypotheses that: (i) the artificial rock pools would support greater species richness than adjacent emergent rock surfaces; and (ii) deeper (12 cm) artificial rock pools would be more productive, and would support greater species richness and different community structure to shallower (5 cm) ones. To assess their potential as surrogate habitats for rocky shore communities, we also compared the artificial rock pools with natural rock pools, testing the hypothesis that: (iii) the artificial rock pools would be equally productive, and would support equivalent species richness and community structure to natural rock pools on nearby rocky shores.

To assess whether the season of installation is an important consideration for planning artificial rock pool interventions, and to assess whether the outcomes would be similar from one year to the next, we replicated the experiment in two different seasons (spring 2012 and autumn 2012) and in two consecutive years (spring 2012 and spring 2013). We chose to conduct the experiments in spring and autumn because these are the seasons in which coastal engineering works are frequently carried out in the UK, to avoid disturbance to overwintering birds and summer tourism (e.g. see planning reports from Centrica Energy 2007, Royal Haskoning 2009, 2014). Although recruitment of intertidal larvae and propagules is known to be liable to stochastic fluctuations (Hawkins and Hartnoll 1982, Underwood and Fairweather 1989, Burrows et al. 2010), predictable seasonal settlement patterns have been recorded for many common rocky shore taxa (e.g. see summary of recrods in Crisp and Southward 1958), along with subsequent effects on successional trajectories (Sousa 1979, Hawkins 1981, Underwood and Anderson 1994, Benedetti-Cecchi 2000, Noël et al. 2009b). Pools installed before and after settlement events may, therefore, be expected to support different communities, on account of differences in initial recruitment. Many intertidal species, such as barnacles (Crisp and Southward 1958, Jenkins et al. 2000), recruit in spring and summer, in between the two seasonal installation dates. This led to two further hypotheses: (iv) the artificial pools installed in spring 2012 would support equivalent species richness but different community structure to the artificial pools installed in autumn 2012, and they would be equally similar to natural rock pools whose trajectories of colonisation started at the same time; and (v) the artificial pools installed in spring 2012 would support equivalent species richness and community structure to the artificial pools installed in spring 2013, and would be equally similar to natural rock pools whose trajectories of colonisation started at the same time.

Finally, we evaluate the management implications of this engineering intervention as a habitat enhancement tool for new and existing coastal defences that are becoming ubiquitous features of urban coastlines globally.

3.2 Materials and methods

3.2.1 Study area

Access to engineered structures for trialling ecological enhancement interventions is difficult to gain due to concerns that manipulations may compromise their functional integrity or lead to liability risks. Therefore, in this study, artificial rock pools were installed in a single intertidal granite breakwater at Tywyn, Wales, UK (52°34.8’N, 04°05.9’W) (Figure 3.1), which was selected on account of secured permissions from the asset manager. The breakwater was constructed in 2010 and is positioned on a sandy shore, backed by a concrete seawall. Artificial pools on the breakwater were compared to natural rock pools at three nearby natural rocky shore sites: Aberystwyth (52°25.1’N, 04°05.2’W), Borth (52°28.8’N, 04°03.3’W) and Clarach (52°26.2’N, 04°04.9’W) (Figure 3.1). All are moderately-exposed bedrock shores of mixed sandstones and mudstones, with shallow gradients and sandy surroundings similar to Tywyn. The three natural rocky shore sites were located to the south of the breakwater due to a lack of suitable sites to the north. Although this was not optimal for the purposes of experimental design, the species pool to the north (Llŷn

Peninsula) and south (natural reefs used in this study) is the same (MarClim data: Hawkins et al., unpublished data). Local coastal processes are characterised by predominantly wave-driven northerly drift of material and highly dynamic beach profiling (Atkins 2009).

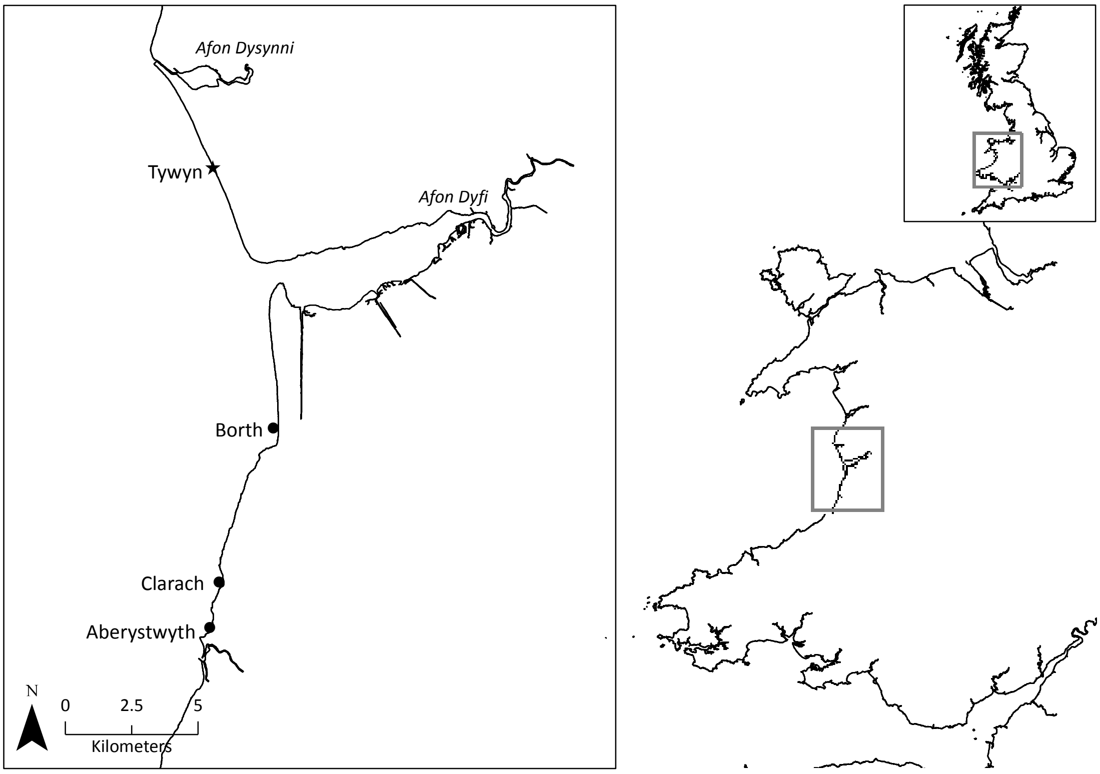

Figure 3.1 Location of breakwater at Tywyn (52°34.8'N, 04°05.9'W) and three natural rocky shore sites at Aberystwyth (52°25.1'N, 04°05.2'W), Borth (52°28.8'N, 04°03.3'W) and Clarach (52°26.2'N, 04°04.9'W), Wales, UK.

3.2.2 Experimental plots

In April 2012 (i.e. spring 2012), 18 artificial rock pools were drilled into the horizontal granite surfaces at mid-shore height on the seaward side of the breakwater, using a diamond-tipped drill corer (Figure 3.2). The pools were designed to replicate small unshaded natural rock pools on nearby rocky shores. However, to make them affordable and easily-replicable, they were necessarily more uniform than natural rock pools (Metaxas and Scheibling 1993); they were all cylindrical with 15 cm diameter and were of two different depths ('deep' 12 cm, 'shallow' 5 cm), randomly assigned with nine replicates of each. Eighteen permanent quadrats were marked out on emergent freely-draining rock surfaces surrounding the drilled pools. Quadrats were of two different sizes, equal to the surface areas of the ‘deep’ and ‘shallow’ pools (i.e. ‘deep’ 742 cm^2, ‘shallow’ 413 cm^2, calculated as the combined surface area of the bottoms and sides of the cylindrical pools), also randomly assigned with nine replicates of each. At each of the three natural rocky shores, ten natural rock pools were selected at mid-shore height for comparison with a subset of ten artificial pools (five ‘deep’, five ‘shallow’, randomly selected). Natural pools were selected to have comparable dimensions to the artificial pools: five ‘deep’ (approximately 15 cm diameter, 12 cm deep) and five ‘shallow’ (approximately 15 cm diameter, 5 cm deep).

To initiate the experiment, all biota were scraped from the experimental plots (i.e. artificial rock pools, emergent surfaces and natural rock pools), and each plot was treated with a flame-gun to remove biofilms and calcareous deposits. A radius of 50 cm around each plot was also cleared and heat-treated to avoid vegetative recolonisation. This was defined as T_{zero} at which point the artificial rock pools, emergent rock surfaces and natural rock pools began their trajectories of colonisation simultaneously.

Figure 3.2 Artificial rock pools (diameter: 15 cm, depth: 12 cm, 5 cm) drill-cored into the horizontal surfaces of an intertidal granite breakwater at Tywyn, Wales, UK.

3.2.3 Temporal replication

The experiment was replicated in October 2012 (i.e. autumn 2012) and again in April 2013 (i.e. spring 2013), with ten additional artificial rock pools on the breakwater (15 cm diameter, five 12 cm deep and five 5 cm deep) and ten additional natural rock pools (approximately 15 cm diameter, five 12 cm deep and five 5 cm deep) at each of the natural rocky shore sites each time. Emergent rock surfaces were not included in these subsequent trials because of logistical constraints.

3.2.4 Measuring biodiversity

The experimental plots (artificial pools, emergent surfaces and natural pools) were surveyed monthly for the first three months and quarterly thereafter, to record counts of mobile fauna and percentage cover of sessile fauna and algae. Taxa were recorded to species level, but where this was not possible without destructive sampling, consistent morphotaxa were used, e.g. 'Lithothamnia' for all calcareous crust species combined. The three experiments initiated in April/spring 2012, October/autumn 2012 and April/spring 2013, were monitored concurrently over 30 months, 24 months and 18 months, respectively, concluding in October/autumn 2014.

3.2.5 Measuring primary productivity

Primary productivity of the algal assemblages in the original April/spring 2012-installed artificial and natural pools was estimated after 30 months (i.e. in October 2014). Primary productivity was estimated using the non-destructive incubation method developed by Kinsey (1985), and employed more recently in intertidal pools by Martins et al. (2007) and Griffin et al. (2010). Community respiratory demand and net primary productivity (i.e. combined photosynthesis and respiration) of rock pool communities were estimated by measuring dissolved oxygen concentrations (mg O_2 l^{-1}; Orion Star A223 DO with polarographic O_2 electrode, Thermo Scientific, Waltham, MA USA) before and after simulated dark and light periods, respectively. Initial dissolved oxygen concentrations were recorded in each pool immediately after they were uncovered by the falling tide (within 15 minutes). The pools were then covered with opaque black polythene sheets for approximately 30 minutes (dark period) before the dissolved oxygen was measured again. The pools were then left exposed to natural daylight for approximately 20 minutes (light period) before a third set of measurements were taken. Dark and light period durations were chosen on the basis of preliminary trials that showed 30 and 20 minutes (respectively) to be long enough for a measurable change in oxygen to occur, whilst not allowing super-saturation, and for the rate of change to be in the linear phase in both cases (Appendix IV). The length of dark and light periods varied slightly for each pool (± 5 minutes), but the rate of change in dissolved oxygen (mg O_2 l^{-1} min^{-1}) was calculated according to the specific periods simulated for each pool (to the nearest minute). Gross primary productivity (GPP) was calculated as:

$$GPP = (R + NPP) \times V, \tag{1}$$

where R is the rate of change in oxygen concentration over the dark period (i.e. respiratory demand; mg O_2 l^{-1} min^{-1}), NPP is the rate of change in oxygen concentration over the light period (i.e. net primary productivity; mg O_2 l^{-1} min^{-1}) and V is the pool volume (l). Thus, GPP per volume and unit of time (mg O_2 l^{-1} min^{-1}) was standardised by rock pool volume (l) to allow direct comparison of photosynthetic rate of the macroalgal communities in each pool (mg O_2 min^{-1}) (Noël et al. 2010).

Productivity was estimated in all 18 artificial rock pools in order to compare ‘deep’ (12 cm) and ‘shallow’ (5 cm) artificial pools. However, due to logistical constraints, for comparison of productivity between artificial and natural pools, only ‘deep’ natural pools were sampled (i.e. five pools at each natural shore site) and compared with a randomly-selected subset of five ‘deep’ artificial pools. Measurements were undertaken on four consecutive days due to the need to sample within 15 minutes of emersion from the tide at four different sites. On all four days, wind velocity was very low and there was no significant difference in mean irradiance levels (Photosynthetic Active Radiation, PAR; PAR ‘Special’ SKP210 1 Channel sensor with SKP200 display meter, Skye Instruments Ltd., Llandrindod Wells, UK), which was measured half-hourly throughout each of the incubations (Kruskal-Wallis: $\chi^2(3) = 0.090$, $P = 0.993$; Appendix IV).

3.2.6 Measuring water chemistry and physical disturbance

Water chemistry parameters (i.e. temperature, pH and salinity) and physical disturbance (i.e. sediment retention and desiccation) were monitored in the original

April/spring 2012-installed artificial rock pools at Tywyn over 30 months (concurrently with biodiversity surveys undertaken between April 2012 and October 2014). Temperature (°C), pH (HI98128 pHep®5 pH/Temperature Tester with 0.01 pH resolution, Hanna Instruments, USA) and salinity (‰, V^2 Refractometer with automatic temperature compensation, TMC Aquarium, London, UK) were measured after gently stirring the pools to breakdown any vertical stratification. The frequency of desiccation events (i.e. depth = 0) was noted, and the volume (V; cm^3) of sand (<2 mm; Wentworth 1922) and coarse sediments (gravel and pebbles, 2 – 64 mm; Wentworth 1922) retained in the pools was estimated as:

$$V = P \times SA \times D, \tag{2}$$

where P is the percentage of the bottom of the pools covered by sediment (%), SA is the surface area of the bottom of the pools (i.e. 176.71 cm^2), and D is the depth (cm) of sediments.

Water chemistry and physical disturbance were monitored in all 18 artificial rock pools in order to compare the habitat provided by 'deep' (12 cm) and 'shallow' (5 cm) artificial pools. These data are analysed and presented in Appendix V.

3.2.7 Data analysis

To address the first hypothesis that artificial rock pools would support greater species richness than emergent rock, the original 18 artificial pools (9 'deep', 9 'shallow', installed in spring 2012) were compared with the 18 quadrats (9 'deep', 9 'shallow') marked out on the emergent rock surfaces of the breakwater after 30 months. Total richness and species accumulation (using presence-absence) were pooled over 'deep' and 'shallow' replicates (n = 18) and plotted over time. Analysis of variance (ANOVA) was used to test for differences in mean species richness between the two habitats. A two-way crossed design was used, with fixed factors Habitat (two levels: pool, surface) and Depth (two levels: 'deep', 'shallow').

To address the second hypothesis that deeper (12 cm) artificial rock pools would be more productive and support greater species richness than, and different community structure to, shallower (5 cm) artificial pools, the original 18 artificial rock pools (nine 'deep', nine 'shallow', installed in spring 2012) were compared after 30 months. Total richness and species accumulation (using presence-absence) were pooled over replicates (n = 9) and plotted over time. ANOVA was used to test for differences in mean GPP and mean species richness between the two habitats. Permutational analysis of variance (PERMANOVA: Anderson 2001) was used to test for differences in multivariate species assemblages, based on 9999 unrestricted permutations of raw data. A one-way design was used for each analysis, with fixed factor Depth (2 levels: 'deep', 'shallow'). Percentage contributions of individual species to dissimilarity between communities were calculated using the SIMPER routine (Clarke 1993). Community structure was compared in 'deep' and 'shallow' artificial pools after 30 months (i.e. in October/autumn 2014), 27 months (i.e. in July/summer 2014), 24 months (i.e. in April/spring 2014) and 21 months (i.e. in January/winter 2014), to investigate their role as habitats at different times of the year.

To address the third hypothesis that the artificial rock pools would support equivalent productivity, species richness and community structure to natural rock pools, a subset of ten of the original artificial pools (five 'deep', five 'shallow', randomly selected from those installed in spring 2012) were compared with the ten original natural pools (five 'deep', five 'shallow') at each of the natural rocky shore sites after 30 months. Total richness and species accumulation were pooled over 'deep' and 'shallow' replicates at each site (n = 10) and plotted over time. ANOVA was used to test for differences in mean GPP and mean species richness. Since there was no significant difference in mean richness between 'deep' and 'shallow' artificial pools, we did not account for the depth treatment when comparing richness in artificial and natural pools. Instead, a two-way asymmetrical nested design was used, with the random factor Site (four levels: Tywyn, Aberystwyth, Borth, Clarach) nested within the fixed upper-level factor Habitat (two levels: artificial, natural), with n = 10 for increased statistical power. GPP was estimated only in 'deep' artificial and natural pools, hence for this analysis, the same two-way nested design was used, but with n = 5. PERMANOVA (with 9999 permutations of residuals under a reduced model) was used to test for differences in multivariate species assemblages between artificial and natural pools. Since 'deep' and 'shallow' artificial rock pool community structures were significantly different, for this analysis Depth was included as a third fixed factor in the asymmetrical nested design, with n = 5. PERMANOVA analyses were performed on the full communities and on the mobile and sessile components separately. Percentage contributions of individual species to dissimilarities between habitat communities (full communities) were calculated using the SIMPER routine. Community structure was compared in artificial and natural rock pools after 30 months (i.e. in October/autumn 2014), 27 months (i.e. in July/summer 2014), 24 months (i.e. in April/spring 2014) and 21 months (i.e. January/winter 2014), to investigate their role as habitats at different times of the year.

To investigate the effect of the season of intervention on artificial rock pool colonisation (hypothesis 4), the same subset of ten original artificial pools (five ‘deep’, five ‘shallow’, randomly selected from those installed in spring 2012) were compared with the ten artificial pools installed in autumn 2012 (five ‘deep’, five ‘shallow’). Total richness and species accumulation were pooled over ‘deep’ and ‘shallow’ replicates (n = 10) and plotted over time (30 months for the spring-installed pools; 24 months for the autumn-installed pools). ANOVA and PERMANOVA were used to test for differences in mean species richness and multivariate species assemblages (respectively) between the two sets of pools at the end of the experiment (i.e. after 30 months for the spring-installed pools; after 24 months for the autumn-installed pools). Comparisons were not made after 24 months of colonisation in *each* set of pools because this would be confounded by the season in which the 24-month surveys were undertaken (i.e. spring for the spring-installed pools; autumn for the autumn-installed pools), which may have led to significant differences that were unassociated with the hypothesis of interest. For the univariate richness analysis, a one-way design was used, with fixed factor Season of installation (2 levels: spring, autumn), again pooled across depths for increased statistical power. For the multivariate analysis, a two-way crossed design was used, with the additional fixed factor Depth (2 levels: ‘deep’, ‘shallow’) and n=5, to account for the observed significant effect of depth on community structure in artificial pools. To assess the relative similarity of spring- and autumn-installed artificial pools to natural rock pools, the ten autumn-installed artificial pools were then compared with the ten natural rock pools whose trajectories of colonisation started at the same time (five ‘deep’, five ‘shallow’, scraped and flamed in autumn 2012), and their similarity was compared with that of the spring 2012-installed artificial and natural pools. Total richness and species accumulation were plotted over time (i.e. 24 months), and mean richness and community structure were compared using ANOVA and PERMANOVA designs as per the previous comparisons between artificial and natural pools (see above).

To investigate whether the installation of artificial rock pools would lead to the same outcomes from year to year (hypothesis 5), the same subset of ten original artificial pools (five 'deep', five 'shallow', randomly selected from those installed in spring 2012) were compared with the ten artificial pools installed in spring 2013 (five 'deep', five 'shallow'). Total richness and species accumulation were pooled over 'deep' and 'shallow' replicates (n = 10) and plotted over time (30 months for the 2012-installed pools; 18 months for the 2013-installed pools). ANOVA and PERMANOVA were used to test for differences in mean species richness and multivariate species assemblages (respectively) between the two sets of pools. For the univariate richness analysis, a one-way design was used, with fixed factor Year of installation (2 levels: 2012, 2013) and n = 10, again pooled across depths for increased statistical power. For the multivariate analysis, a two-way crossed design was used, with the additional fixed factor Depth (2 levels: 'deep', 'shallow') and n=5, to account for the observed significant effect of depth on community structure in artificial pools. The pools were compared after 18 months of colonisation in each (i.e. the terminal time-point for the 2013-installed pools), and also at the end of the experiment in October 2014 (i.e. after 30 months for the 2012-installed pools; after 18 months for the 2013-installed pools) to account for the potential confounding effect of the year in which the surveys took place. To assess the relative similarity of 2012- and 2013-installed artificial pools to natural rock pools, the ten spring 2013-installed artificial pools were compared with the ten natural rock pools whose trajectories of colonisation started at the same time (five 'deep', five 'shallow', scraped and flamed in spring 2013), and their similarity was compared with that of spring 2012-installed artificial and natural pools. Total richness and species accumulation were plotted over time (i.e. 18 months), and mean richness and community structure were compared using ANOVA and PERMANOVA designs as per the previous comparisons between artificial and natural pools (see above).

A summary table outlining which replicates were used for each analysis is included in Appendix VI. All univariate analyses were carried out in R (R Core Team 2012). Multivariate analyses were carried out in PRIMER v6 & PERMANOVA+

(PRIMER-E Ltd. Version 6, 2006) and were based on Bray-Curtis similarity matrices of fourth-root transformed data. Prior to univariate analyses, homogeneity of variance was confirmed using Levene's test. Prior to multivariate analyses, homogeneity of multivariate dispersions was tested using the PERMDISP routine (Anderson 2006). Although PERMANOVA is more flexible with regard to assumptions than univariate parametric statistics, homogeneity of dispersions is implicit in the construction of the pseudo-F statistic (Anderson 2001). This can be considered an advantage in multivariate analyses (Clarke 1993) and can be built into the null hypothesis of 'no difference between groups'. Where heterogeneity was indicated alongside *non-significant* PERMANOVA main effects in this study (i.e. comparisons between spring 2012-installed artificial and natural rock pool mobile assemblages in April and July 2014; and comparison between spring 2013-installed artificial and natural rock pool communities in October 2014), this was considered inconsequential to the null hypothesis of interest. In these cases, there was no significant difference between groups, *despite* differences in multivariate dispersions. For two analyses (i.e. comparison between spring 2012-installed artificial and natural rock pool communities in April 2014; and comparison between autumn 2012-installed artificial and natural rock pool communities in October 2014), heterogeneity was indicated alongside *significant* PERMANOVA main effects. To aid interpretation in these cases, non-metric Multidimensional Scaling (MDS) plots were inspected, and in both cases, clear multivariate locational differences were evident, suggesting that significant results were not exclusively caused by differences in multivariate dispersions. The results from these two analyses should, however, be interpreted with due caution. For the asymmetrical PERMANOVA analyses, there were not enough possible permutations to perform a reasonable test of significance. Therefore, Monte Carlo *P* values were used as a more meaningful, but approximate, alternative (Anderson and Robinson 2003).

3.3 Results

3.3.1 Comparing artificial pools with emergent surfaces on the breakwater

Collectively, the artificial rock pool habitats consistently supported more species than the surrounding emergent rock surfaces (Figure 3.3a). Initially, total species richness increased rapidly, reaching an asymptote after three months on the emergent rock surfaces (13 species) and after six months in the artificial pools (24 species). Although total richness appeared to then level off (but with some seasonal fluctuations), species accumulation curves (Figure 3.3b) revealed that the total species pool supported by both habitats did, in fact, continue to rise steadily over time. Species accumulation on the emergent rock surfaces, however, appeared to have reached an asymptote after nine months (20 species), and no new species had colonised since July 2013 (15 months: 21 species). Conversely, for the pools, an asymptote had not yet been reached (30 months: 47 species; Figure 3.3b). This suggests that the artificial rock pools not only supported greater species richness overall, but also a greater number of transient and ephemeral taxa, which were utilising the novel habitats at different times of year.

After 30 months, the mean species richness in the artificial pools (‘deep’: 6.0 ± 0.6 SE, ‘shallow’: 7.1 ± 0.6 SE) was significantly greater than on the adjacent rock surfaces (‘deep’: 4.8 ± 0.4 SE, ‘shallow’: 4.8 ± 0.3 SE) ($F_{1,32}$ 13.003, $P = 0.001$; Figure 3.3c). There was no significant effect of depth ($F_{1,32}$ 1.270, $P = 0.268$) and no interaction ($F_{1,32}$ 1.270, $P = 0.268$).

The rock pools increased the richness of most taxonomic groups (with the exception of barnacles and bivalves) and provided habitat for several major groups that were absent from the surrounding granite rock surfaces (i.e. fish, ascidians, bryozoans, hydroids and sponges) (Figure 3.4).

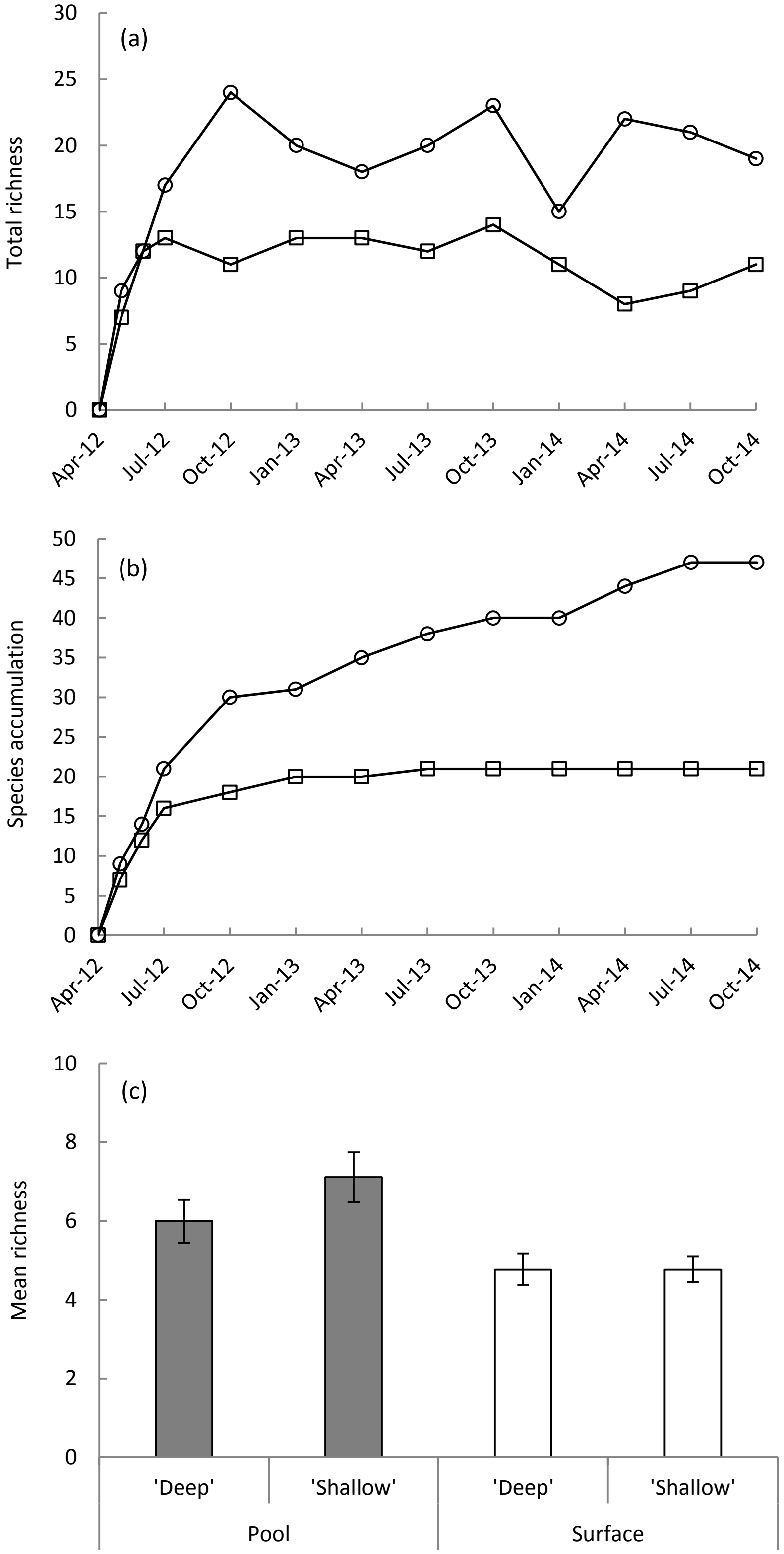

Figure 3.3 *(*a) Total species richness and (b) cumulative number of species recorded in spring 2012-installed artificial rock pools (○) and on emergent rock surfaces (□) over 30 months (April 2012 – October 2014); data pooled over 18 replicates (9 'deep', 9 'shallow') in each case. (c) Mean (± SE) species richness recorded in 'deep' and 'shallow' artificial pools (grey bars) and on emergent surfaces of equivalent surface area (white bars) after 30 months (i.e. in October 2014); n = 9.

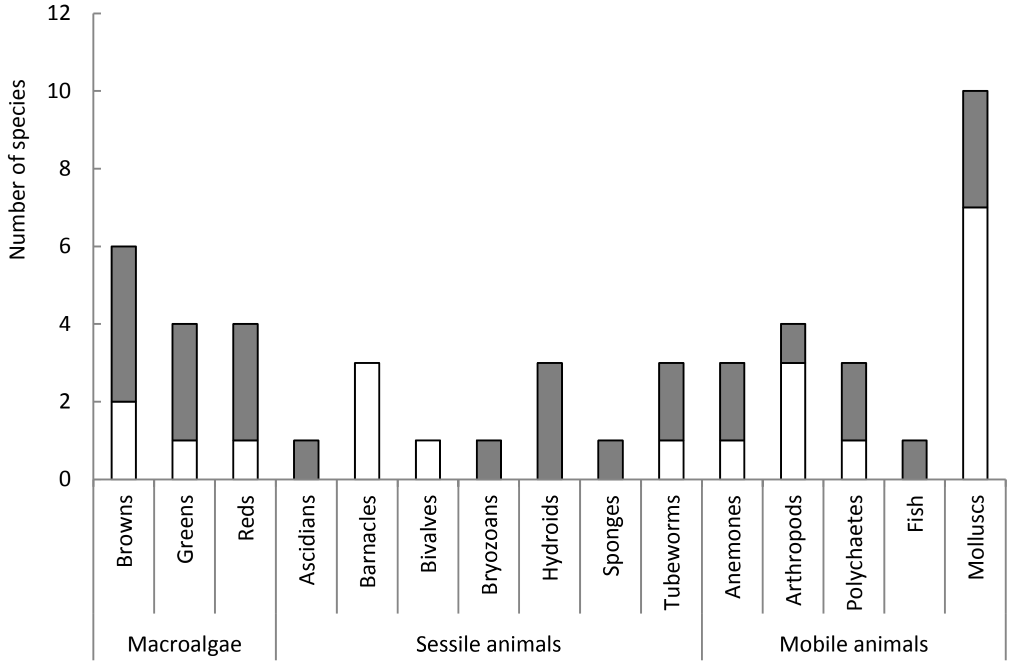

Figure 3.4 Total number of species in major taxa recorded on emergent rock surfaces (white bars) and *additional* species recorded exclusively in artificial rock pools (grey bars) over 30 months (April 2012 – October 2014). Data pooled over 18 replicates (9 'deep', 9 'shallow').

3.3.2 Comparing deep and shallow artificial rock pools

Collectively, the 'deep' (12 cm) and 'shallow' (5 cm) artificial rock pools consistently supported similar species richness over time (Figure 3.5a), and species accumulation in both habitats followed similar trajectories, which had not yet reached an asymptote (Figure 3.5b). There was no significant difference in mean species richness ($F_{1,16}$ 1.747, P = 0.205; Figure 3.3c) or mean GPP ($F_{1,16}$ 0.113, P = 0.741; Figure 3.6) between 'deep' and 'shallow' artificial pools after 30 months. Community structure was, however, significantly different (Pseudo-$F_{1,16}$ 2.860, P(perm) = 0.025; Figure 3.7a). 'Deep' artificial pools supported higher abundances of the filamentous red alga, *Polysiphonia* sp. (11.1% contribution to dissimilarity), the keel tubeworms, *Spirobranchus* spp. (8.3% contribution), and beadlet anemones, *Actinia equina* (7.9%), whilst 'shallow' pools supported higher abundances of a different tube-building worm, *Sabellaria alveolata* (12.6%), the mussel, *Mytilus edulis* (8.1%), the limpet, *Patella vulgata* (7.7%), and the green alga, *Ulva intestinalis* (7.5%) (Table 3.1). Several proportionally-rarer species were absent from the deeper pools, e.g. the black-footed limpet, *Patella depressa*, and the polychaetes *Eulalia viridis* and *Lanice conchilega*.

In addition, we were interested in the effect of depth on the role of artificial pools as habitats at different times of the year. Community structure was also significantly different between 'deep' and 'shallow' artificial pools after 27 months of colonisation (i.e. in July/summer 2014; Pseudo-$F_{1,16}$ 2.375, P(perm) = 0.024; Figure 3.7b). At this time of year, the ephemeral brown alga, *Spongonema tomentosum* (which was more abundant in 'deep' pools), and the green alga, *Cladophora* sp. (more abundant in 'shallow' pools), contributed more to community differences (7.7% and 7.1%, respectively) than *Polysiphonia* sp. (3.6%) and *U. intestinalis* (4.3%), and 'deep' pools supported more shannies, *Lipophrys pholis* (Table 3.2). After 24 months and 21 months of colonisation (i.e. in April/spring and January/winter 2014, respectively), however, there was no significant difference in community structure between 12 cm and 5 cm deep artificial pools (April/spring 2014: Pseudo-$F_{1,16}$ 1.171, P(perm) = 0.322, Figure 3.7c; January/winter 2014: Pseudo-$F_{1,16}$ 2.041, P(perm) = 0.101, Figure 3.7d).

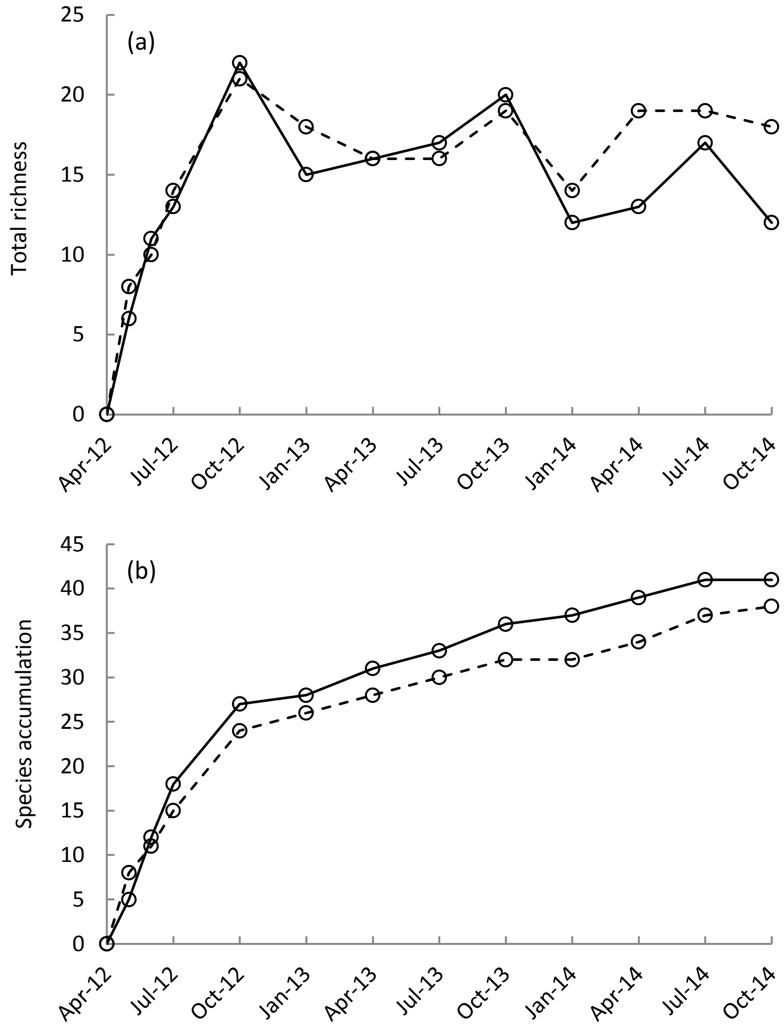

Figure 3.5 *(*a) Total species richness and (b) cumulative number of species recorded in spring 2012-installed ‘deep’ (solid lines) and ‘shallow’ (dashed lines) artificial rock pools over 30 months (April 2012 – October 2014); data pooled over 9 replicates in each case.

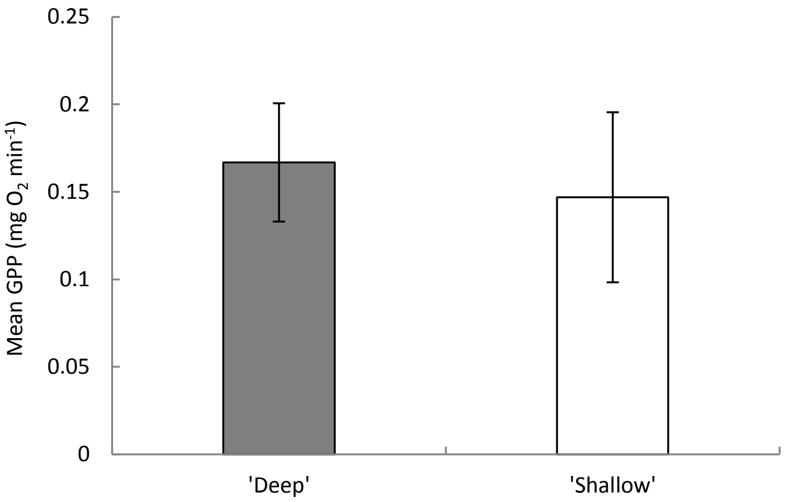

Figure 3.6 Mean (± SE) gross primary productivity (GPP) recorded in 'deep' (grey bars) and 'shallow' (white bars) artificial rock pools at Tywyn after 30 months (i.e. in October 2014); n = 9.

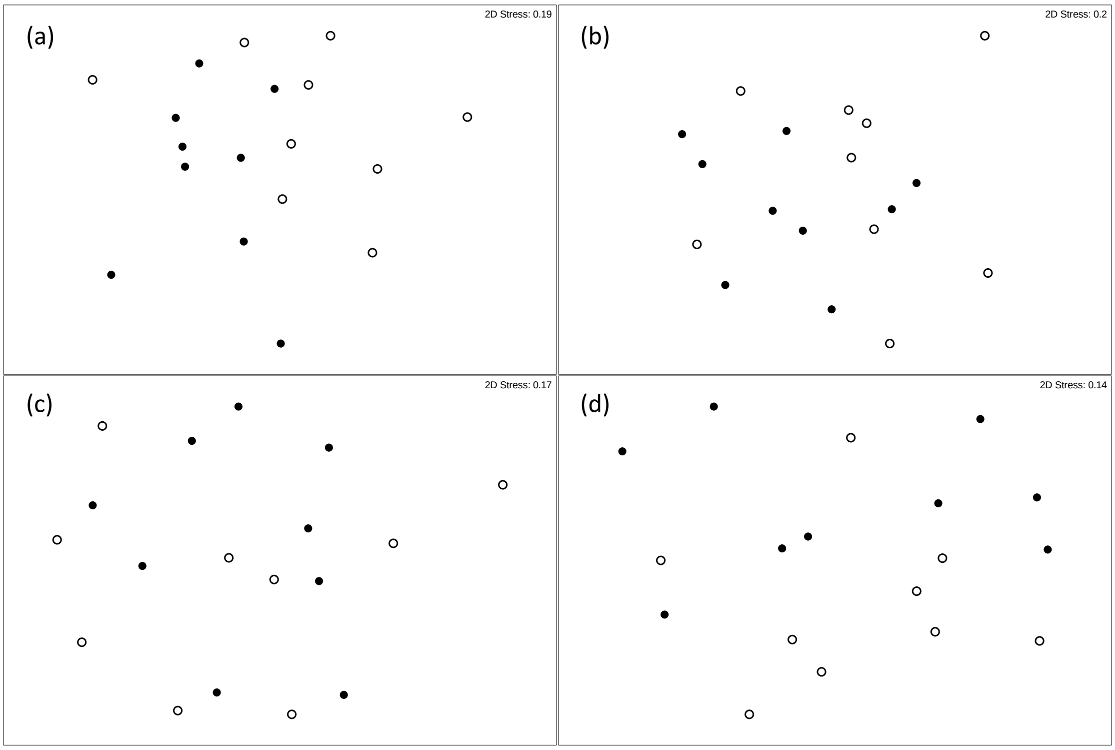

Figure 3.7 nMDS ordinations of multivariate species assemblages in spring 2012-installed 'deep' (●) and 'shallow' (○) artificial rock pools: (a) after 30 months, i.e. in October/autumn 2014; (b) after 27 months, i.e. July/summer 2014; (c) after 24 months, i.e. April/spring 2014; and (d) after 21 months, i.e. January/winter 2014.

Table 3.1 Differences (< and >) in mean abundances (counts (c) or percentage cover (%)) of species recorded in spring 2012-installed 'deep' (n = 9) and 'shallow' (n = 9) artificial rock pools after 30 months, i.e. in October/autumn 2014. Species listed in order of their contribution (%) to the dissimilarities between multivariate species assemblages (SIMPER analysis on full community).

%: percent contribution to multivariate dissimilarity; Diss/SD: dissimilarity divided by standard deviation of contributions across all pairs of samples (measure of consistency of contribution)

Average dissimilarity = 42.8 %					
Species	**'Deep' pools**		**'Shallow' pools**	**%**	**Diss/ SD**
Sabellaria alveolata %	6.0	<	25.6	12.6	1.1
Polysiphonia sp. %	9.9	>	5.0	11.1	1.3
Spirobranchus spp. %	12.2	>	4.6	8.3	1.3
Mytilus edulis %	0	<	1.6	8.1	0.9
Actinia equina c	0.9	>	0.2	7.9	1.2
Patella vulgata c	2.0	<	2.3	7.7	1.1
Ulva intestinalis %	10.4	<	19.4	7.5	1.4
Austrominius modestus %	0.4	=	0.4	6.3	0.9
Semibalanus balanoides %	0.2	<	0.8	5.4	0.8
Leptothecata %	0.6	<	0.9	4.7	0.6
Chthamalus montagui %	0	<	0.7	4.4	0.7
Spongonema tomentosum %	2.2	>	1.7	4.3	0.5
Bryopsis sp. %	0.6	=	0.6	3.2	0.5
Patella depressa c	0	<	0.2	2.5	0.5
Fucus vesiculosus %	0	<	0.1	1.6	0.4
Eulalia viridis c	0	<	0.1	1.2	0.4
Lanice conchilega c	0	<	0.1	1.2	0.4
Nucella lapillus c	0.1	>	0	1.1	0.4
Littorina littorea c	0	<	0.1	1.1	0.4

Table 3.2 Differences (< and >) in mean abundances (counts (c) or percentage cover (%)) of species recorded in spring 2012-installed ‘deep’ (n = 9) and ‘shallow’ (n = 9) artificial rock pools after 27 months, i.e. in July/summer 2014. Species listed in order of their contribution (%) to the dissimilarities between multivariate species assemblages (SIMPER analysis on full community).

%: percent contribution to multivariate dissimilarity; Diss/SD: dissimilarity divided by standard deviation of contributions across all pairs of samples (measure of consistency of contribution)

Average dissimilarity = 49.1 %					
Species	**‘Deep’ pools**		**‘Shallow’ pools**	**%**	**Diss/ SD**
Spirobranchus spp. %	7.1	>	1.9	9.8	1.6
Sabellaria alveolata %	0.8	<	7.1	8.5	1.2
Spongonema tomentosum %	11.9	>	4.2	7.7	1.1
Actinia equina c	1.9	>	0.2	7.7	1.4
Cladophora sp. %	1.6	<	2.9	7.1	1.1
Lipophrys pholis c	2.6	>	0.7	6.7	1.2
Semibalanus balanoides %	1.7	<	3.9	6.4	1.2
Portunidae c	0.9	<	1.0	5.8	1.0
Patella vulgata c	3.0	>	2.2	5.7	1.0
Mytilus edulis %	0	<	1.7	5.1	0.8
Ulva intestinalis %	14.8	<	23.8	4.3	1.4
Leptothecata %	1.7	>	0	4.2	0.7
Chaetomorpha linum %	0.2	<	1.1	3.7	0.6
Polyplacophora c	0.1	<	0.4	3.6	0.7
Polysiphonia sp. %	1.2	>	1.1	3.6	0.6
Patella depressa c	0.1	<	0.2	2.4	0.6
Austrominius modestus %	0.2	>	0.1	2.1	0.5
Nucella lapillus c	0	<	0.3	1.8	0.5
Ceramium sp. %	1.1	>	0	1.5	0.4
Fucus vesiculosus %	0	<	0.2	1.3	0.4
Lanice conchilega c	0	<	0.2	1.0	0.4

3.3.3 Comparing artificial pools with natural rock pools

Collectively, the artificial and natural rock pools consistently supported similar species richness over time (Figure 3.8a), and species accumulation at all sites followed similar trajectories, which had not yet reached an asymptote (Figure 3.8b). After 30 months, there was no significant difference in mean species richness ($F_{1,36}$ 1.298, P = 0.373; Figure 3.8c) or mean GPP ($F_{1,16}$ 0.151, P = 0.735; Figure 3.9) between the artificial pools and the natural pools. Community structure was, however, significantly different in terms of full communities (Pseudo-$F_{1,32}$ 4.441, P(mc) = 0.027; Figure 3.10a), mobile faunal assemblages (Pseudo-$F_{1,32}$ 6.138, P(mc) = 0.030; Figure 3.10b) and sessile assemblages (Pseudo-$F_{1,32}$ 4.362, P(mc) = 0.047; Figure 3.10c). The dissimilarity in mobile assemblages between artificial and natural pools (average Bray-Curtis dissimilarity: 67.90; Figure 3.10b) was less pronounced than the dissimilarity in sessile assemblages (average Bray-Curtis dissimilarity: 73.79; Figure 3.10c). SIMPER analysis (Table 3.3) attributed 50% of the dissimilarity between the artificial and natural rock pool communities to two calcareous algae, encrusting Lithothamnia (13.4% contribution) and *Corallina officinalis* (10.9%), which were present in the natural pools but absent from the artificial ones, and also to *S. alveolata* (7.3%), *Spirobranchus* spp. (6.7%), *U. intestinalis* (5.8%) and *Polysiphonia* sp. (5.3%), which were all more abundant in the artificial pools. In addition, many of the proportionally-rarer species recorded in the natural pools were absent from the artificial ones (Table 3.3).

Comparing the role of artificial and natural pools as habitats at different times of the year, community structure was also significantly different in natural and artificial pools throughout the rest of 2014 (July/summer: Pseudo-$F_{1,32}$ 3.524, P(mc) = 0.034; April/spring: Pseudo-$F_{1,32}$ 4.248, P(mc) = 0.027; January/winter: Pseudo-$F_{1,32}$ 4.293, P(mc) = 0.033). At these times, however, the dissimilarity between artificial and natural pools was attributable to sessile fauna and algae (July/summer: Pseudo-$F_{1,32}$ 4.348, P(mc) = 0.029; April/spring: Pseudo-$F_{1,32}$ 5.839, P(mc) = 0.019; January/winter: Pseudo-$F_{1,32}$ 6.406, P(mc) = 0.021), whereas the mobile faunal assemblages were not significantly different (July/summer: Pseudo-$F_{1,32}$ 2.217, P(mc) = 0.169; April/spring: Pseudo-$F_{1,32}$ 2.484, P(mc) = 0.155; January/winter: Pseudo-$F_{1,32}$ 1.440, P(mc) = 0.328). SIMPER analyses revealed that Lithothamnia, *C. officinalis*, and *S. alveolata* were consistently high contributors to the dissimilarity in artificial and natural community structures, along with a variety of other species that varied in their relative contributions at different times of year (Table 3.4). Earlier in the year (i.e. in January/winter and April/spring), one of the highest contributors to community differences (12.6% and 11.7%, respectively) was *M. edulis*, which was more abundant in the artificial pools than in natural pools. This was the result of substantial settlement of *M. edulis* spat at Tywyn in July 2012 (*pers. obs.*), the majority of which had disappeared by July 2014. In all analyses, there was no interaction between Habitat and Depth, suggesting that the dissimilarities (or, in some cases, similarities) between 'deep' artificial and natural pools corresponded with dissimilarities (or similarities) between 'shallow' artificial and natural pools.

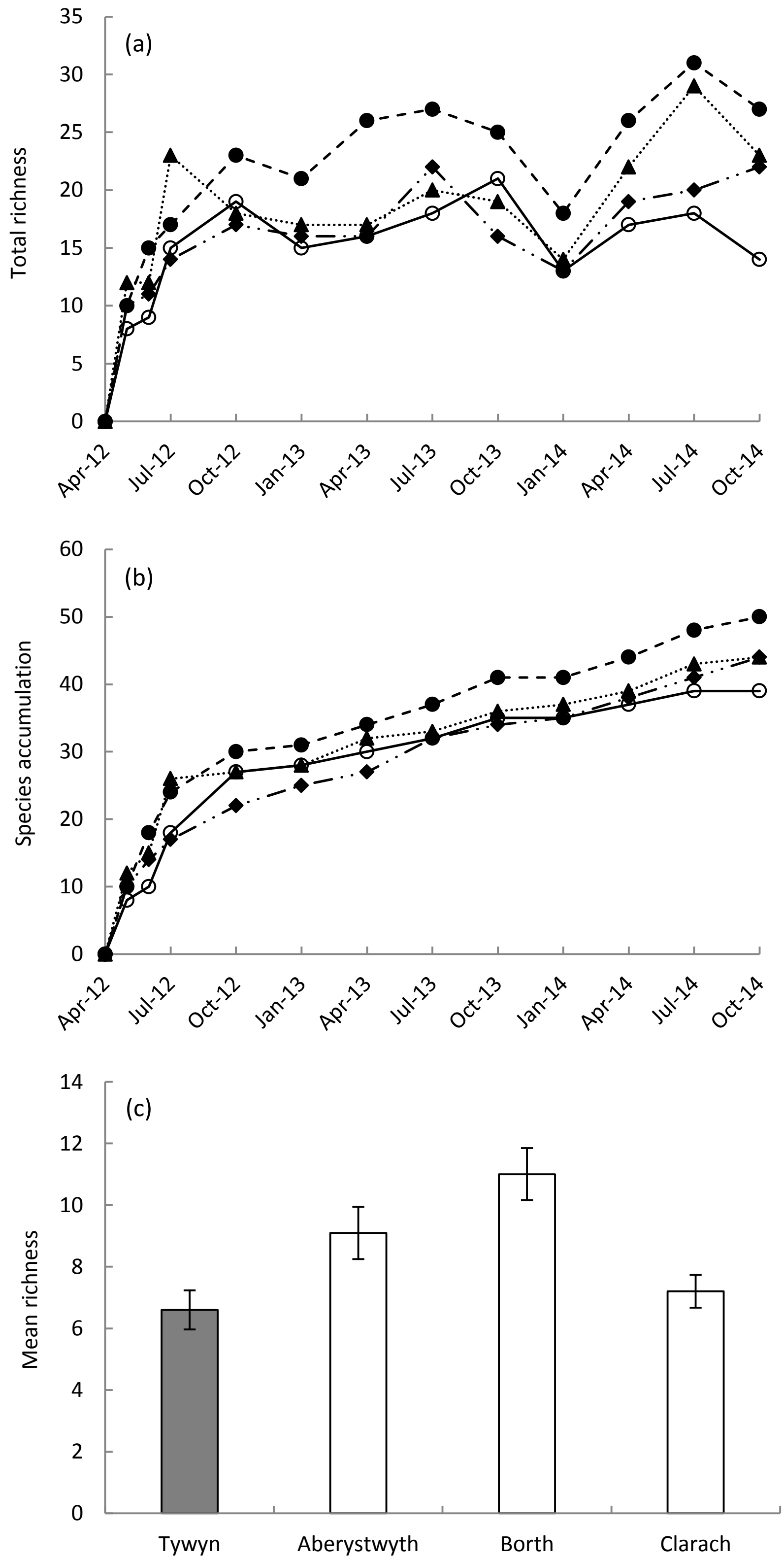

Figure 3.8 *(*(a) Total species richness and (b) cumulative number of species recorded in spring 2012-installed artificial rock pools at Tywyn (○, solid lines) and natural rock pools at Aberystwyth (▲, dotted lines), Borth (●, dashed lines) and Clarach (◆, compound lines) over 30 months (April 2012 – October 2014); data pooled over 10 replicates (5 'deep', 5 'shallow') in each case. (c) Mean (± SE) species richness recorded in artificial (grey bars) and natural (white bars) rock pools after 30 months (i.e. in October 2014); n = 10.

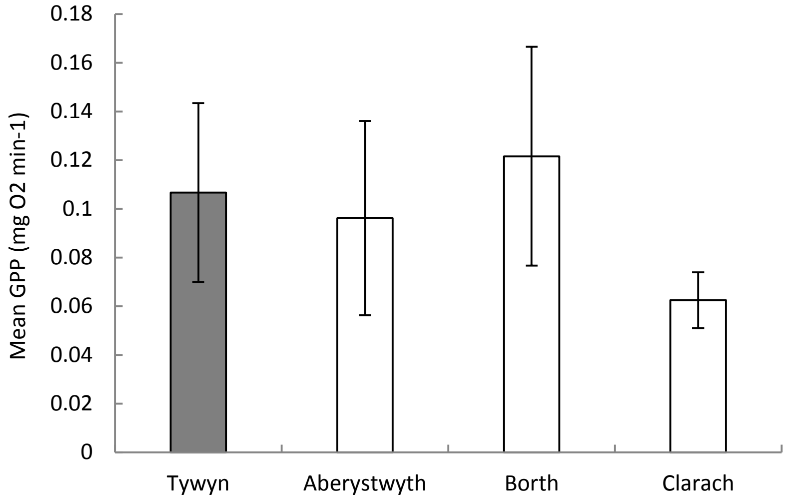

Figure 3.9 Mean (± SE) gross primary productivity (GPP) recorded in 'deep' artificial rock pools at Tywyn (grey bars) and 'deep' natural rock pools at Aberystwyth, Borth and Clarach (white bars) after 30 months (i.e. in October 2014); n = 5.

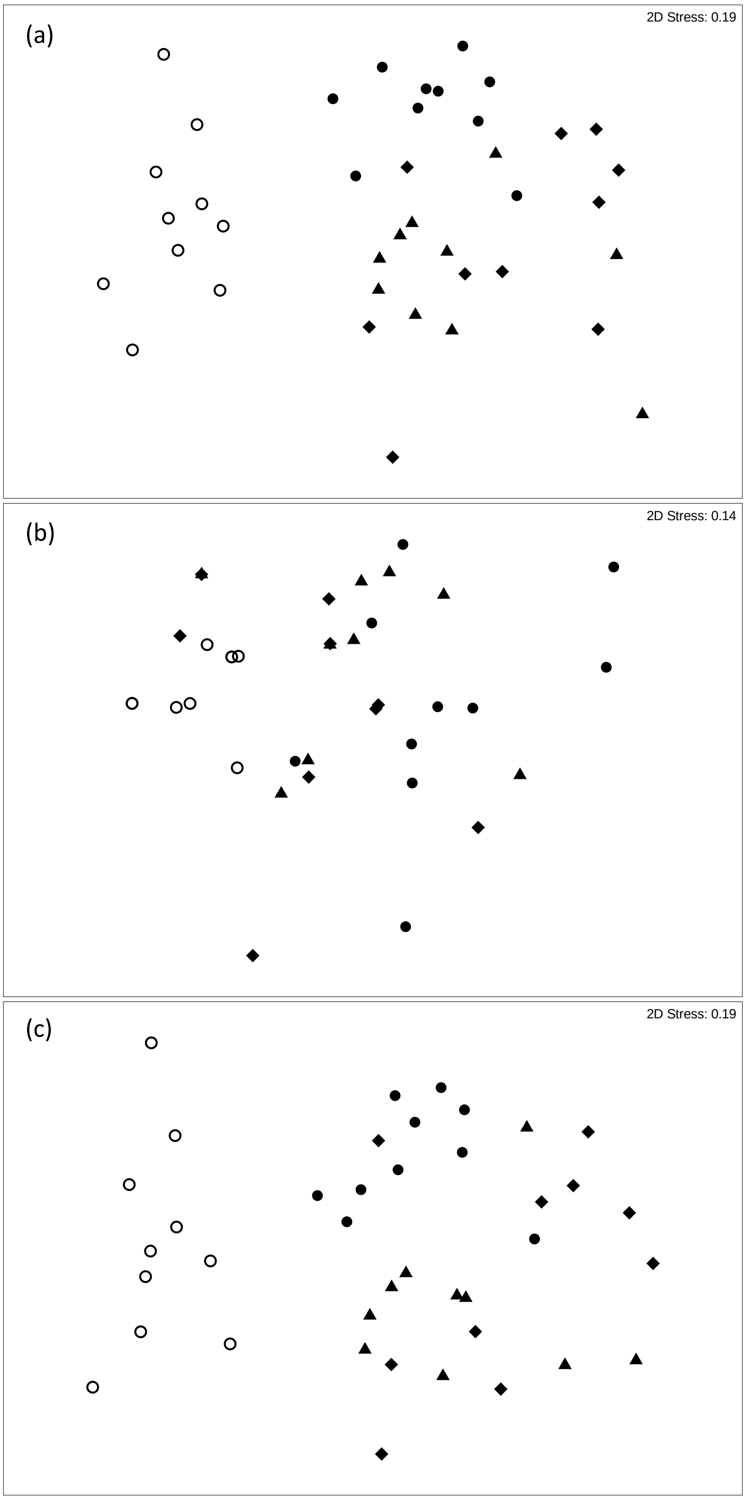

Figure 3.10 nMDS ordinations of multivariate species assemblages in spring 2012-installed artificial rock pools at Tywyn (○) and natural rock pools at Aberystwyth (▲), Borth (●) and Clarach (◆) after 30 months: (a) full community; (b) mobile faunal assemblages; and (c) sessile assemblages.

Table 3.3 Differences (< and >) in mean abundances (counts (c) or percentage cover (%)) of species recorded in spring 2012-installed artificial rock pools (n = 10) and natural rock pools (n = 30) after 30 months, i.e. in October/autumn 2014. Species listed in order of their contribution (%) to the dissimilarities between multivariate species assemblages (SIMPER analysis on full community).

%: percent contribution to multivariate dissimilarity; Diss/SD: dissimilarity divided by standard deviation of contributions across all pairs of samples (measure of consistency of contribution)

Average dissimilarity = 71.9 %					
Species	**Natural pools**		**Artificial pools**	**%**	**Diss/ SD**
Lithothamnia %	28.1	>	0	13.4	3.5
Corallina officinalis %	12.6	>	0	10.9	3.3
Sabellaria alveolata %	3.6	<	9.9	7.3	1.4
Spirobranchus spp. %	1.8	<	4.3	6.7	1.3
Ulva intestinalis %	3.5	<	7.6	5.8	1.2
Polysiphonia sp. %	1.6	<	2.9	5.3	1.1
Gibbula umbilicalis c	2.0	>	0	5.1	1.2
Patella vulgata c	4.3	>	3.2	4.5	1.0
Semibalanus balanoides %	1.1	>	0.8	3.9	1.0
Littorina littorea c	1.6	>	0.1	3.8	0.9
Austrominius modestus %	0.3	<	0.7	3.6	1.0
Actinia equina c	0	<	0.6	3.4	0.9
Leptothecata %	1.8	>	1.0	3.4	0.7
Chondrus crispus %	2.8	>	0	3.3	0.7
Spongonema tomentosum %	1.9	>	1.0	2.9	0.6
Chthamalus sp. %	0.7	>	0.5	2.1	0.7
Fucus vesiculosus %	0.7	>	0	2.1	0.6
Patella depressa c	0.3	>	0.2	1.8	0.6
Osmundea sp. %	0.6	>	0	1.5	0.5
Ceramium sp. %	0.3	>	0	1.2	0.4
Lipophrys pholis c	0.2	>	0	1.1	0.4
Mytilus edulis %	0	<	0.3	0.9	0.3
Anurida maritima c	0.3	>	0	0.8	0.4
Scytosiphon lomentaria %	0.2	>	0	0.7	0.3
Littorina saxatilis c	0.1	>	0	0.6	0.3
Portunidae c	0.1	>	0	0.6	0.3
Ascidiacea %	0.1	>	0	0.5	0.3
Rhizoclonium riparium %	<0.1	>	0	0.3	0.2
Porifera crust yellow %	0.1	>	0	0.3	0.2
Nucella lapillus c	0.2	>	0	0.3	0.2
Mastocarpus stellatus %	0.1	>	0	0.3	0.2
Porifera crust orange %	<0.1	>	0	0.3	0.2
Lomentaria articulata %	0.1	>	0	0.2	0.2
Mysida c	<0.1	>	0	0.2	0.2
Littorina obtusata c	<0.1	>	0	0.2	0.2

Eulalia viridis c	<0.1	>	0	0.2	0.2
Patella ulyssiponensis c	<0.1	>	0	0.2	0.2
Polyplacophora c	<0.1	>	0	0.2	0.2
Palaemon elegans c	<0.1	>	0	0.2	0.2
Phorcus lineatus c	<0.1	>	0	0.2	0.2

Table 3.4 Differences (< and >) in mean abundances (counts (c) or percentage cover (%)) of species recorded in spring 2012-installed artificial rock pools (n = 10) and natural rock pools (n = 30) after 27 months, 24 months and 21 months, i.e. in July/summer 2014, April/spring 2014 and January/winter 2014, respectively. Species listed in order of their contribution (%) to the dissimilarities between multivariate species assemblages (SIMPER analysis on full community), with cut-off at 50 % cumulative contribution.

%: percent contribution to multivariate dissimilarity; Diss/SD: dissimilarity divided by standard deviation of contributions across all pairs of samples (measure of consistency of contribution)

July 2014. Average dissimilarity = 73.4 %					
Species	**Natural pools**		**Artificial pools**	**%**	**Diss/ SD**
Lithothamnia %	18.4	>	0	9.8	2.8
Corallina officinalis %	10.1	>	0	8.1	2.5
Ulva intestinalis %	6.4	<	25.3	6.8	1.3
Spongonema tomentosum %	0.8	<	3.6	4.9	1.1
Gibbula umbilicalis c	1.8	>	0	4.5	1.3
Rhizoclonium riparium %	2.8	>	0	4.3	1.2
Cladophora sp. %	1.9	<	2.4	4.3	1.1
Sabellaria alveolata %	2.3	<	2.5	4.1	1.0
Lipohrys pholis c	0.9	<	2.1	4.1	1.1
April 2014. Average dissimilarity = 80.3 %					
Species	**Natural pools**		**Artificial pools**	**%**	**Diss/ SD**
Mytilus edulis %	<0.1	<	5.4	12.6	2.0
Lithothamnia %	12.0	>	0	11.6	2.6
Corallina officinalis %	7.2	>	0	8.6	1.7
Gibbula umbilicalis c	1.5	>	0.1	6.1	1.3
Patella vulgata c	3.6	<	5.8	5.4	0.7
Littorina littorea c	1.2	>	0.4	5.4	0.9
Sabellaria alveolata %	0.9	<	1.5	5.3	0.9
January 2014. Average dissimilarity = 78.1 %					
Species	**Natural pools**		**Artificial pools**	**%**	**Diss/ SD**
Lithothamnia %	15.4	>	0	13.8	2.3
Mytilus edulis %	0	<	3.9	11.7	1.9
Corallina officinalis %	7.2	>	0	11.7	2.5
Sabellaria alveolata %	2.6	>	2.3	7.7	1.3
Actinia equina c	0	<	1.1	6.2	1.0

3.3.4 Comparing artificial pools installed in spring 2012 and autumn 2012

The rapid increases in total richness and species accumulation that were observed in the spring 2012-installed artificial rock pools were delayed in the autumn 2012-installed artificial pools, until after the initial winter months (Figures 3.11a, b). However, after 12 months of colonisation, the autumn 2012-installed pools supported similar total richness and species accumulation over time as those installed in the spring, even though the latter had been colonised over a longer period (18 months). There was no significant difference in mean richness between the two sets of pools at the end of the experiment (i.e. after 30 months for the spring 2012-installed pools; after 24 months for the autumn 2012-installed pools; $F_{1,18}$ 1.203, P = 0.287; Figure 3.11c). Community structure was, however, significantly different (Pseudo-$F_{1,16}$ 3.221, P(perm) = 0.005; Figure 3.12). SIMPER analysis attributed 50% of the dissimilarity to higher abundances of hydroids (Leptothecata; 11.7%), *S. alveolata* (10.9%), *Polysiphonia* sp. (9.9%), *Spirobranchus* spp. (8.8 %) and the acorn barnacle, *Austrominius modestus* (7.7%), in the autumn 2012-installed pools (Table 3.5).

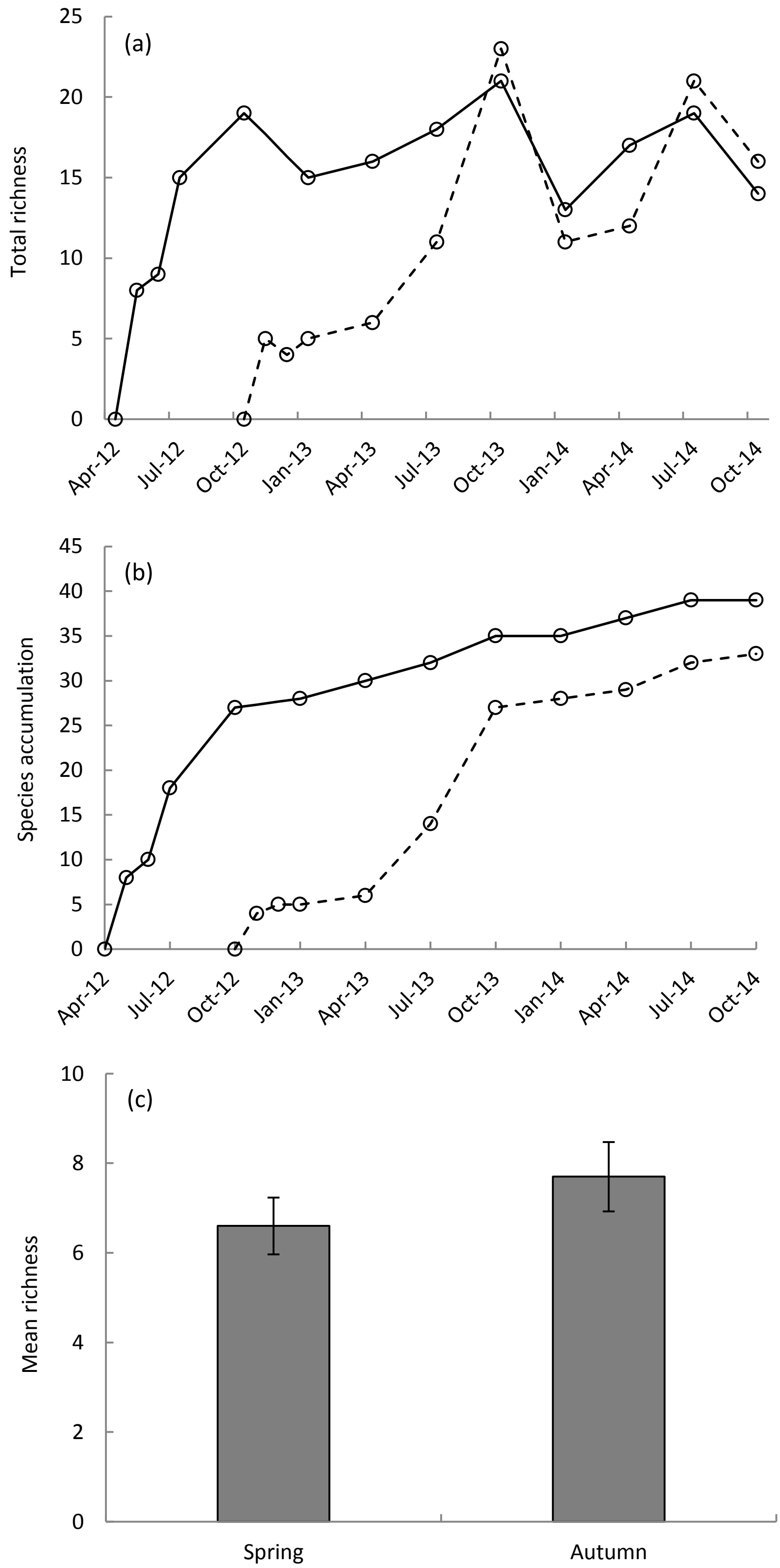

Figure 3.11 (a) Total species richness and (b) cumulative number of species recorded in spring 2012-installed artificial rock pools (solid lines) and autumn 2012-installed artificial rock pools (dashed lines) over 30 months and 24 months, respectively; data pooled over 10 replicates (5 'deep', 5 'shallow') in each case. (c) Mean (± SE) species richness in spring- and autumn-installed artificial pools after 30 and 24 months, respectively (i.e. in October 2014); n = 10.

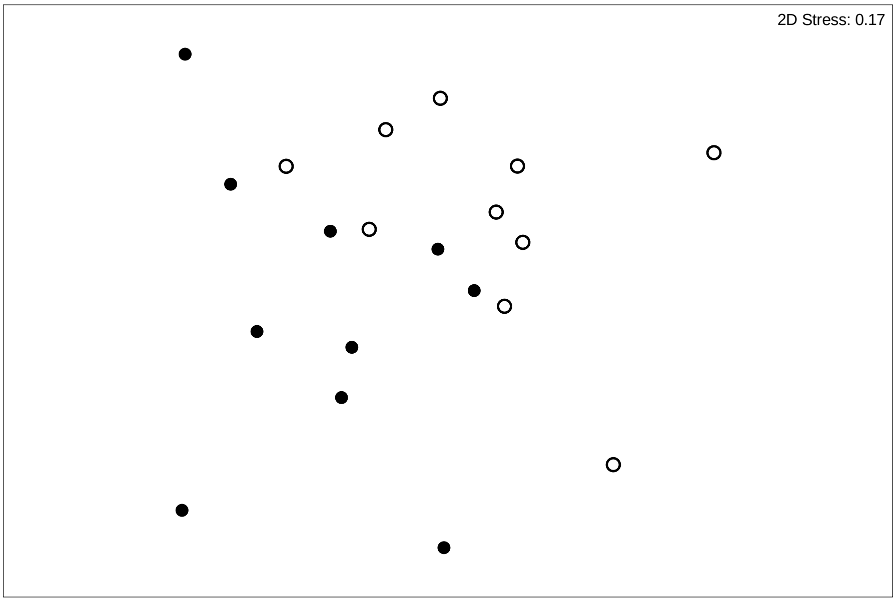

Figure 3.12 nMDS ordination of multivariate species assemblages in spring 2012-installed artificial rock pools (●) and autumn 2012-installed artificial rock pools (○) at Tywyn at the end of the experiment in October 2014 (i.e. after 30 months for spring-installed pools; after 24 months for autumn-installed pools).

Table 3.5 Differences (< and >) in mean abundances (counts (c) or percentage cover (%)) of species recorded in spring 2012-installed artificial rock pools (n = 10) and autumn 2012-installed artificial rock pools (n = 10) in October 2014, i.e. after 30 months for spring-installed pools; after 24 months for autumn-installed pools. Species listed in order of their contribution (%) to the dissimilarities between multivariate species assemblages (SIMPER analysis on full community).

%: percent contribution to multivariate dissimilarity; Diss/SD: dissimilarity divided by standard deviation of contributions across all pairs of samples (measure of consistency of contribution)

Average dissimilarity = 44.3 %					
Species	**Spring 2012**		**Autumn 2012**	**%**	**Diss/ SD**
Leptothecata %	1.0	<	7.0	11.7	1.1
Sabellaria alveolata %	9.9	<	21.6	10.9	1.1
Polysiphonia sp. %	2.9	<	7.0	9.9	1.1
Spirobranchus spp. %	4.3	<	5.2	8.8	1.1
Austrominius modestus %	0.7	<	2	7.7	1.1
Semibalanus balanoides %	0.8	<	1.5	7.7	1.1
Patella vulgata c	3.2	<	3.3	7.1	0.9
Spongonema tomentosum %	1.0	<	3.0	6.1	0.7
Actinia equina c	0.6	>	0.3	6.0	1.0
Ulva intestinalis %	7.6	<	11.3	5.5	1.4
Plumulariidae %	0	<	3.0	3.5	0.5
Chthamalus sp. %	0.5	>	0	3.4	0.6
Mytilus edulis %	0.3	<	0.4	2.9	0.5
Ceramium sp. %		<	1.0	2.6	0.5
Patella depressa c	0.2	>	0	2.0	0.5
Scytosiphon lomentaria %	0	<	0.1	1.3	0.3
Polyplacophora c	0	<	0.1	1.1	0.3
Nucella lapillus c	0	<	0.2	1.0	0.3
Littorina littorea c	0.1	>	0	0.9	0.3

The delayed initial colonisation that was observed in the autumn 2012-installed artificial rock pools (Figures 3.11a, b) was not observed to the same extent in the natural pools whose trajectories of colonisation began at the same time (Figures 3.13a, b). Whereas the spring 2012-installed artificial pools supported similar richness and pattern of species accumulation to natural pools throughout the study (Figures 3.8a, b), the autumn 2012-installed artificial pools initially supported lower richness and a smaller species pool compared with natural pools (Figures 3.13a, b). However, after 12 months of colonisation, the autumn 2012-installed artificial pools supported similar richness over time to natural pools (Figure 3.13a), and their species accumulation followed similar trajectories, which had not yet reached an asymptote (Figure 3.13b). Further, there was no significant difference in mean richness between autumn 2012-installed artificial and natural pools at the end of the experiment (i.e. after 24 months; $F_{1,36}$ 0.157, P = 0.730; Figure 3.13c). As for the spring 2012-installed pools, community structure in autumn 2012-installed artificial rock pools was significantly different to natural rock pools whose trajectories of colonisation had started simultaneously (Pseudo-$F_{1,32}$ 5.576, P(mc) = 0.011; Figure 3.14). The magnitude of dissimilarity between the autumn 2012-installed artificial and natural pools was similar to that observed between the spring 2012-installed artificial and natural pools (average Bray-Curtis dissimilarities: 72.00 and 71.93, respectively; Figure 3.14).

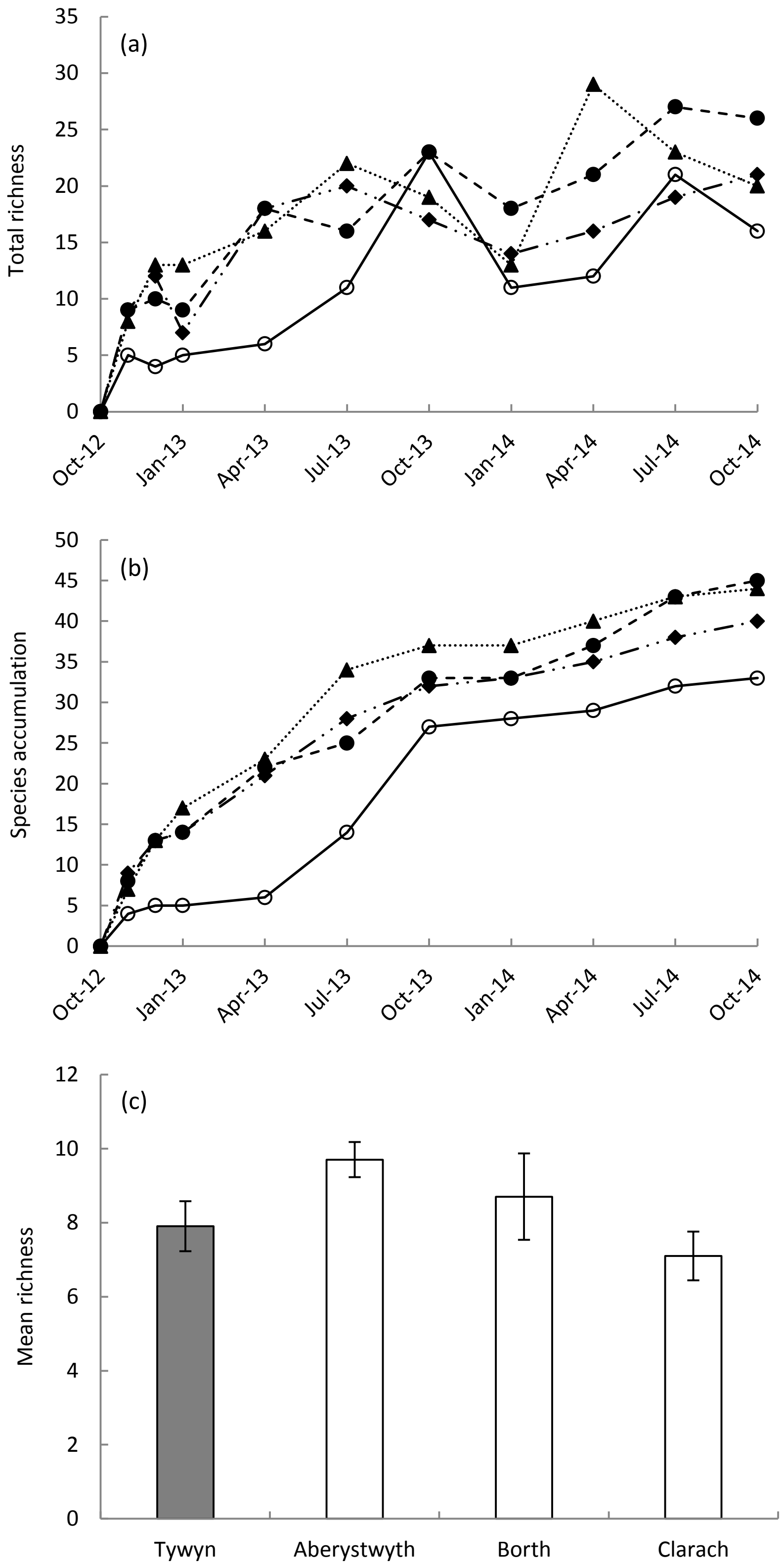

Figure 3.13 (a) Total species richness and (b) cumulative number of species recorded in autumn 2012-installed artificial rock pools at Tywyn (○, solid lines) and natural pools at Aberystwyth (▲, dotted lines), Borth (●, dashed lines) and Clarach (◆, compound lines) over 24 months (October 2012 – October 2014); data pooled over 10 replicates (5 'deep', 5 'shallow') in each case. (c) Mean (± SE) species richness in autumn-installed artificial (grey bars) and natural (white bars) pools after 24 months (i.e. in October 2014); n = 10.

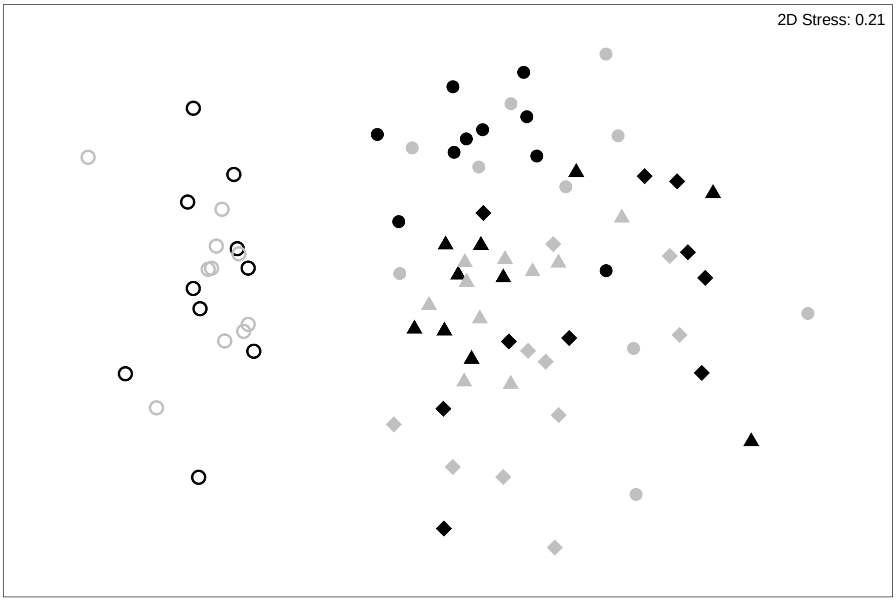

Figure 3.14 nMDS ordination of multivariate species assemblages in artificial rock pools at Tywyn (○) and natural rock pools at Aberystwyth (▲), Borth (●) and Clarach (◆) in October 2014. Black symbols represent pools whose colonisation started in spring 2012 (after 30 months); grey symbols represent pools whose colonisation started in autumn 2012 (after 24 months).

3.3.5 Comparing artificial pools installed in spring 2012 and spring 2013

Total richness and species accumulation over time followed similar trajectories in the artificial rock pools installed in spring 2012 and spring 2013 (Figures 3.15a, b). Furthermore, there was no significant difference in mean richness between the two sets of pools after 18 months of colonisation in each ($F_{1,18}$ 0.562, P = 0.463; Figure 3.15c). However, when comparing the two sets of pools at the end of the experiment (i.e. after 30 months for the spring 2012-installed pools; after 18 months for the spring 2013-installed pools), mean richness was significantly higher in the spring 2013-installed pools ($F_{1,18}$ 4.569, P = 0.047; Figure 3.15c), despite having been colonised over a shorter time period. This appears to follow a recent decline in richness in the spring 2012-installed pools (Figure 3.15a), and may be an artefact rather than a real treatment effect of the time of installation. Community structure was significantly different between spring 2012-installed and spring 2013-installed artificial pools, both after 18 months of colonisation in each (Pseudo-$F_{1,16}$ 11.790, P(perm) < 0.001; Figure 3.16a), and also when compared at the end of the experiment (Pseudo-$F_{1,16}$ 3.690, P(perm) = 0.004; Figure 3.16b). SIMPER analysis attributed almost 50% of the dissimilarity after 18 months to higher abundances of *M. edulis* in the spring 2012-installed pools (14.4% contribution), and higher abundances of Leptothecata (8.9%), *Spirobranchus* spp. (8.4%), *Polysiphonia* sp. (6.7%) and the acorn barnacle, *Semibalanus balanoides* (6.3%) in the spring 2013-installed pools (Table 3.6). As before, the contribution of *M. edulis* to significant differences was the result of a substantial settlement event that occurred prior to the spring 2013 intervention (*pers. obs.*). The dissimilarity at the end of the experiment (i.e. removed from temporal survey bias) was also attributed to higher abundances of Leptothecata (13.1%), *Polysiphonia* sp. (9.2%) and *S. balanoides* (9.3%) in the spring 2013-installed pools, along with *A. modestus* (8.3%) (Table 3.7). *Spirobranchus* spp. (4.9%) and *M. edulis* (2.5%) no longer contributed highly.

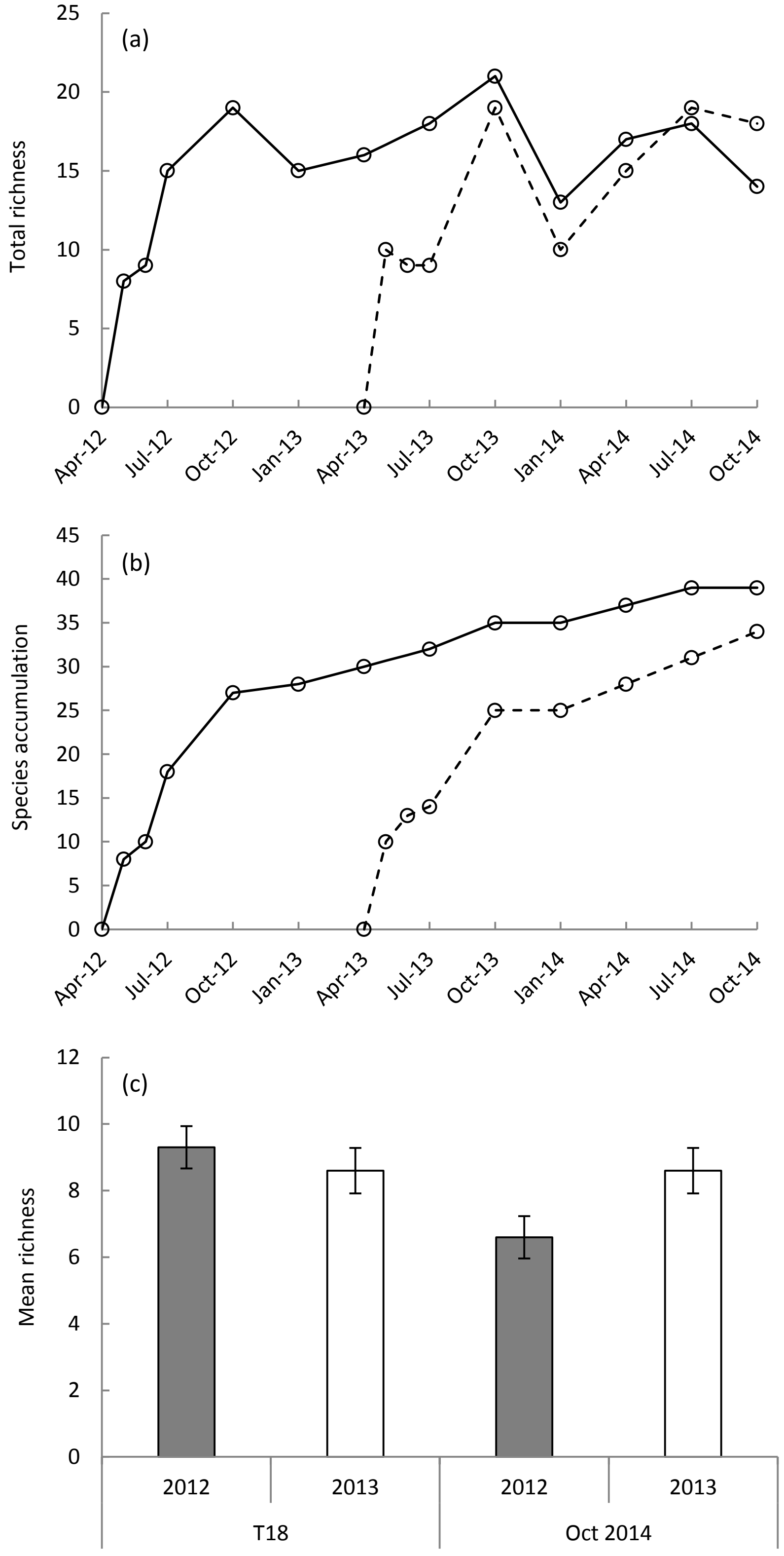

Figure 3.15 (a) Total species richness and (b) cumulative number of species recorded in spring 2012-installed artificial rock pools (solid lines) and spring 2013-installed artificial rock pools (dashed lines) over 30 months and 18 months, respectively; data pooled over 10 replicates (five 'deep', 5 'shallow') in each case. (c) Mean (± SE) species richness in 2012- (grey bars) and 2013-installed (white bars) artificial rock pools after 18 months colonisation in each, and at the end of the experiment in October 2014; n = 10.

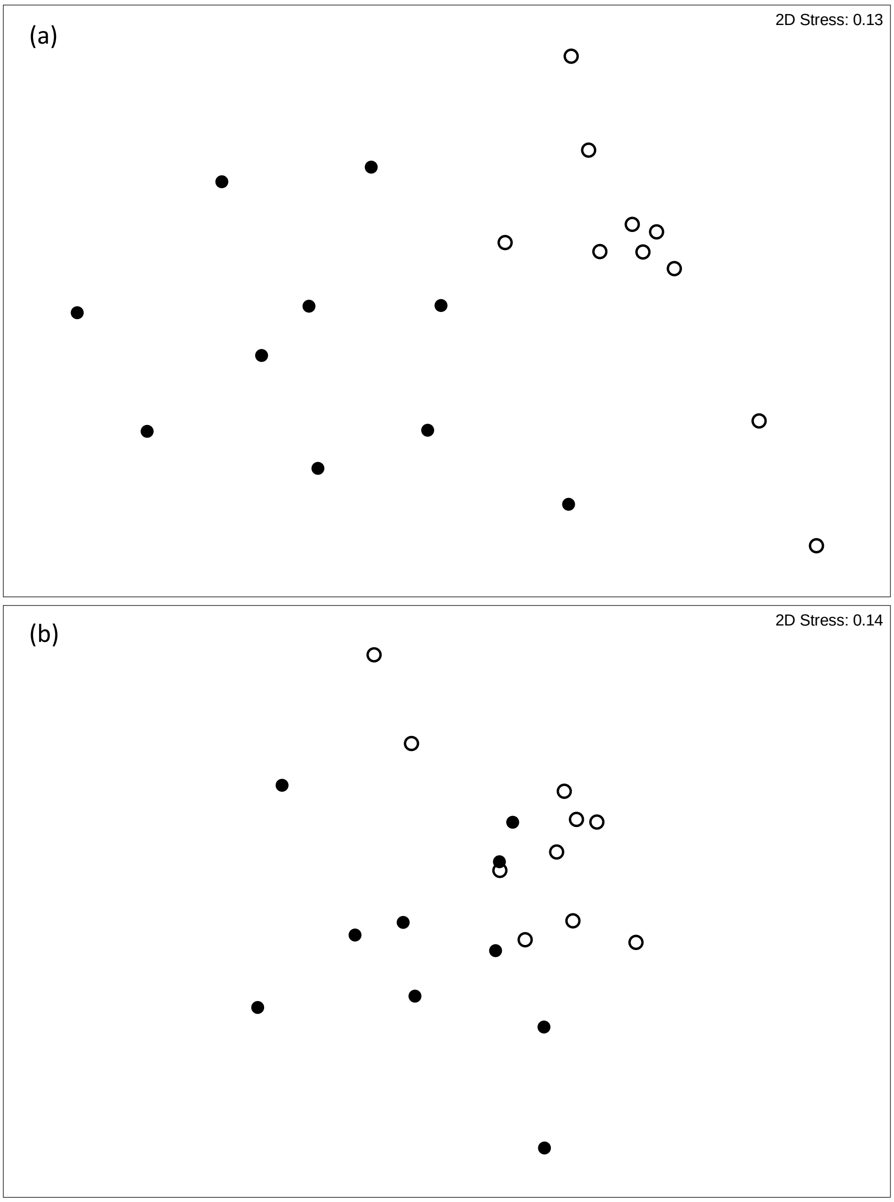

Figure 3.16 nMDS ordinations of multivariate species assemblages in spring 2012-installed artificial rock pools (●) and spring 2013-installed artificial rock pools (○) at Tywyn: (a) after 18 months colonisation in each (i.e. October 2013 for 2012-installed pools; October 2014 for 2013-installed pools); and (b) in October 2014 (i.e. after 30 months for 2012-installed pools; after 18 months for 2013-installed pools).

Table 3.6 Differences (< and >) in mean abundances (counts (c) or percentage cover (%)) of species recorded in spring 2012-installed artificial rock pools (n = 10) and spring 2013-installed artificial rock pools (n = 10) after 18 months (i.e. in October 2013 for 2012-installed pools; in October 2014 for 2013-installed pools). Species listed in order of their contribution (%) to the dissimilarities between multivariate species assemblages (SIMPER analysis on full community).

%: percent contribution to multivariate dissimilarity; Diss/SD: dissimilarity divided by standard deviation of contributions across all pairs of samples (measure of consistency of contribution)

Average dissimilarity = 55.2 %					
Species	**Spring 2012**		**Spring 2013**	**%**	**Diss/ SD**
Mytilus edulis %	29.4	>	0.2	14.4	2.9
Leptothecata %	0.2	<	7.9	8.9	1.7
Spirobranchus spp. %	1.7	<	6.5	8.4	1.8
Polysiphonia sp. %	1.9	<	6.3	6.7	1.2
Semibalanus balanoides %	0.5	<	3.2	6.3	1.5
Littorina littorea c	2.7	>	0	5.8	1.1
Sabellaria alveolata %	5.2	<	7.6	5.5	1.3
Plumulariidae %	2.8	<	3.5	5.0	0.9
Ceramium sp. %	1.7	>	0.5	5.0	1.1
Spongonema tomentosum %	0	<	6.0	4.9	0.8
Actinia equina c	0.9	>	0.5	4.3	1.1
Patella vulgata c	3.6	<	4.8	4.2	0.9
Austrominius modestus %	5.1	>	2.9	4.2	1.0
Nucella lapillus c	0.6	>	0.1	3.4	0.8
Ulva intestinalis %	8.3	<	8.9	3.1	1.3
Lipophrys pholis c	0.2	=	0.2	1.8	0.6
Phaeophyceae %	0.2	>	0	1.4	0.5
Actinia fragacea c	0.2	>	0	1.3	0.5
Fucus vesiculosus %	1.5	>	0	1.3	0.3
Lomentaria articulata %	0	<	0.2	0.8	0.3
Lithothamnia %	0	<	0.1	0.7	0.3
Sagartia troglodytes c	0.1	>	0	0.7	0.3
Littorina obtusata c	0.1	>	0	0.6	0.3
Ascidiacea %	0.1	>	0	0.6	0.3
Patella depressa c	0	<	0.1	0.6	0.3

Table 3.7 Differences (< and >) in mean abundances (counts (c) or percentage cover (%)) of species recorded in spring 2012-installed artificial rock pools (n = 10) and spring 2013-installed artificial rock pools (n = 10) in October 2014 (i.e. after 30 months for 2012-installed pools; after 18 months for 2013-installed pools). Species listed in order of their contribution (%) to the dissimilarities between multivariate species assemblages (SIMPER analysis on full community).

%: percent contribution to multivariate dissimilarity; Diss/SD: dissimilarity divided by standard deviation of contributions across all pairs of samples (measure of consistency of contribution)

Average dissimilarity = 44.3 %					
Species	**Spring 2012**		**Spring 2013**	**%**	**Diss/ SD**
Leptothecata %	1.0	<	7.9	13.1	1.5
Semibalanus balanoides %	0.8	<	3.2	9.3	1.3
Sabellaria alveolata %	9.9	>	7.6	9.3	1.1
Polysiphonia sp. %	2.9	<	6.3	9.2	1.1
Austrominius modestus %	0.7	<	2.9	8.3	1.3
Spongonema tomentosum %	1.0	<	6.0	7.9	0.8
Patella vulgata c	3.2	<	5.0	6.8	0.9
Actinia equina c	0.6	>	0.5	5.9	1.0
Spirobranchus spp. %	4.3	<	6.5	4.9	1.1
Plumulariidae %	0	<	3.5	4.9	0.6
Ulva intestinalis %	7.6	<	8.9	4.6	1.3
Chthamalus sp. %	0.5	>	0	3.3	0.6
Patella depressa c	0.2	>	0.1	2.6	0.6
Mytilus edulis %	0.3	>	0.2	2.5	0.5
Ceramium sp. %	0	<	0.5	2.1	0.3
Lomentaria articulata %	0	<	0.2	1.3	0.3
Lithothamnia %	0	<	0.1	1.1	0.3
Lipophrys pholis c	0	<	0.2	1.1	0.3
Nucella lapillus c	0	<	0.1	0.9	0.3
Littorina littorea c	0.1	>	0	0.9	0.3

Total richness and species accumulation over time followed similar trajectories in the artificial rock pools installed in spring 2013 and the natural rock pools whose colonisation started at the same time (Figures 3.17a, b). Further, there was no significant difference in mean richness between spring 2013-installed artificial and natural pools at the end of the experiment (i.e. after 18 months; $F_{1,36}$ 1.978, P = 0.295; Figure 3.17c). Unlike the spring 2012-installed pools, however, community structure in spring 2013-installed artificial rock pools was not significantly different to community structure in the corresponding natural rock pools (Pseudo-$F_{1,32}$ 2.698, P(mc) = 0.080; Figure 3.18). There was, however, some evidence of dissimilarity in the spring 2013-installed artificial and natural pools, similar to that observed between the spring 2012-installed artificial and natural pools (average Bray-Curtis dissimilarities: 60.48 and 71.93, respectively; Figure 3.18). Closer inspection of the relative species abundances in the spring 2013-installed artificial and natural pools (Table 3.8) revealed lower abundances of *C. officinalis* and Lithothamnia, and fewer proportionally-rarer species in the spring 2013 natural pools, compared with the spring 2012 natural pools (Table 3.3). This may partly explain the non-significant result; the spring 2013 natural pools were at an earlier stage of succession than the spring 2012 natural pools, thus the differences between natural and artificial pools was less marked.

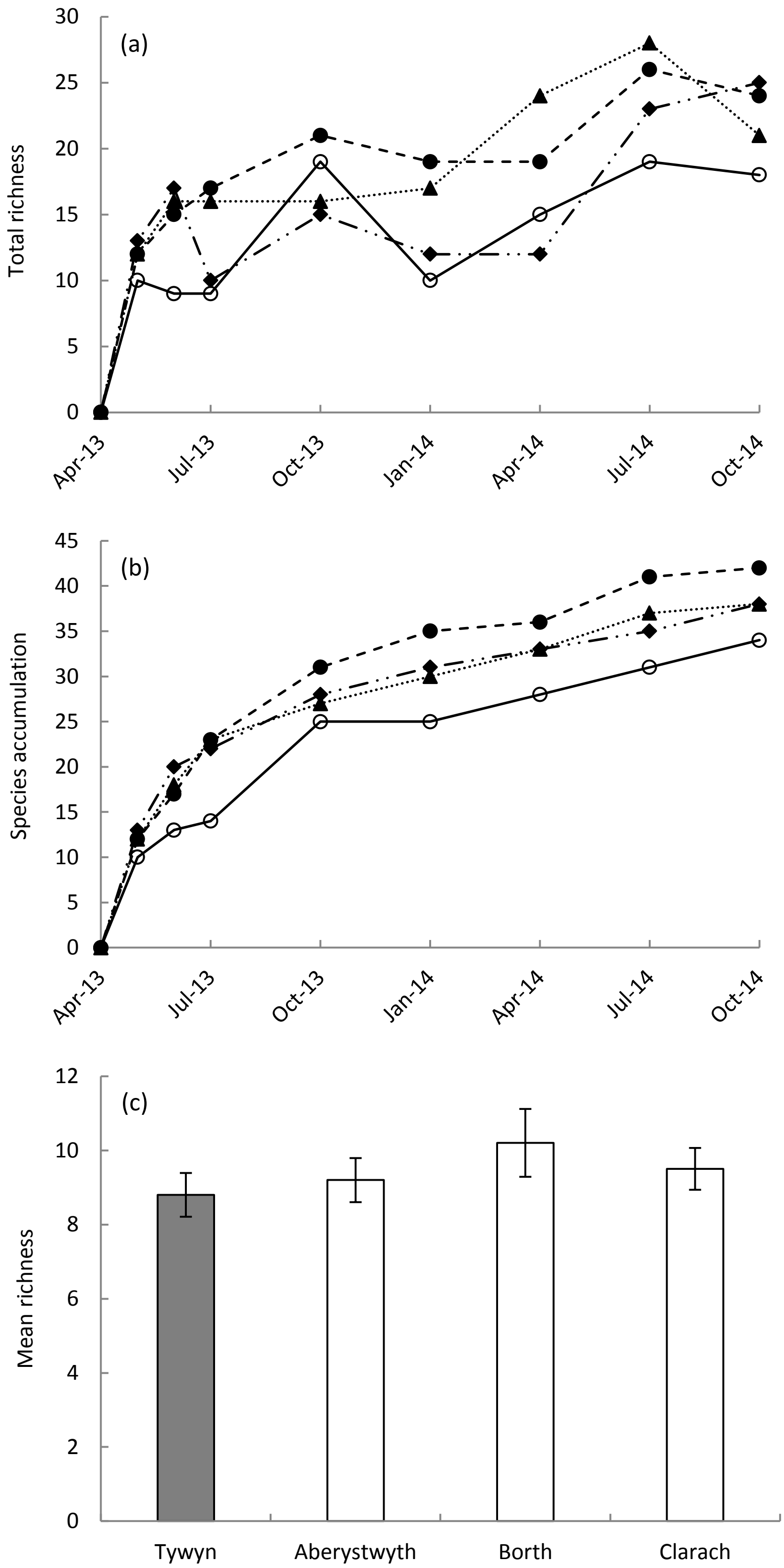

Figure 3.17 (a) Total species richness and (b) cumulative number of species recorded in spring 2013-installed artificial rock pools at Tywyn (○, solid lines) and natural rock pools at Aberystwyth (▲, dotted lines), Borth (●, dashed lines) and Clarach (◆, compound lines) over 18 months (April 2013 – October 2014); data pooled over 10 replicates (5 'deep', 5 'shallow') in each case. (c) Mean (± SE) species richness recorded in 2013-installed artificial (grey bars) and natural (white bars) after 18 months (i.e. in October 2014); n = 10.

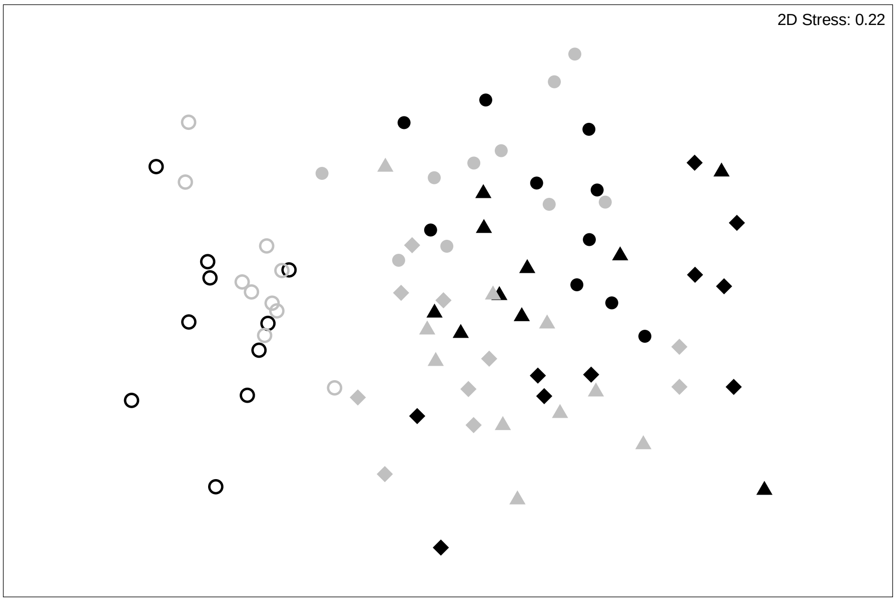

Figure 3.18 nMDS ordination of multivariate species assemblages in artificial rock pools at Tywyn (○) and natural rock pools at Aberystwyth (▲), Borth (●) and Clarach (◆) in October 2014. Black symbols represent pools whose colonisation started in spring 2012 (after 30 months), grey symbols represent pools whose colonisation started in spring 2013 (after 18 months).

Table 3.8 Differences (< and >) in mean abundances (counts (c) or percentage cover (%)) of species recorded in spring 2013-installed artificial rock pools (n = 10) and natural rock pools (n = 30) after 18 months. Species listed in order of their contribution (%) to the dissimilarities between multivariate species assemblages (SIMPER analysis on full community).

%: percent contribution to multivariate dissimilarity; Diss/SD: dissimilarity divided by standard deviation of contributions across all pairs of samples (measure of consistency of contribution)

Average dissimilarity = 60.5 %

Species	**Natural pools**		**Artificial pools**	**%**	**Diss/ SD**
Lithothamnia %	14.5	>	0.1	10.8	3.0
Corallina officinalis %	4.1	>	0	7.2	1.8
Sabellaria alveolata %	1.2	<	7.6	7.1	1.5
Leptothecata %	6.0	<	7.9	7.0	1.4
Spirobranchus spp. %	2.1	<	6.5	6.3	1.4
Ulva intestinalis %	2.8	<	8.9	5.9	1.2
Spongonema tomentosum %	3.7	<	6.0	5.6	1.0
Austrominius modestus %	0.6	<	2.9	5.4	1.4
Polysiphonia sp. %	3.2	<	6.3	5.3	1.1
Patella vulgata c	7.7	>	4.8	4.6	1.0
Semibalanus balanoides %	2.1	<	3.2	4.4	1.1
Gibbula umbilicalis c	1.0	>	0	3.1	0.8
Plumulariidae %	0	<	3.5	3.0	0.6
Anurida maritima c	1.9	>	0	2.8	0.6
Littorina littorea c	0.5	>	0	2.3	0.7
Chondrus crispus %	1.4	>	0	2.1	0.6
Actinia equina c	0	<	0.5	2.0	0.6
Osmundea sp. %	0.6	>	0	1.8	0.5
Fucus vesiculosus %	0.7	>	0	1.8	0.5
Ceramium sp. %	0.2	<	0.5	1.8	0.5
Patella depressa c	0.3	>	0.1	1.6	0.5
Lipophrys pholis c	0.1	<	0.2	1.2	0.5
Nucella lapillus c	0.1	=	0.1	1.1	0.5
Mytilus edulis %	0.1	<	0.2	1.0	0.4
Lomentaria articulata %	0	<	0.2	0.8	0.3
Scytosiphon lomentaria %	0.2	>	0	0.6	0.3
Littorina obtusata c	0.1	>	0	0.5	0.3
Cladophora sp. %	0.1	>	0	0.5	0.3
Porifera crust yellow %	0.1	>	0	0.4	0.3
Patella ulyssiponensis c	0.1	>	0	0.4	0.3
Littorina saxatilis c	<0.1	>	0	0.3	0.2
Rhizoclonium riparium %	<0.1	>	0	0.3	0.2
Bryopsis sp. %	<0.1	>	0	0.2	0.2
Cordylecladia erecta %	<0.1	>	0	0.2	0.2
Portunidae c	<0.1	>	0	0.2	0.2

Chthamalus sp. %	<0.1	>	0	0.2	0.2
Porifera crust orange %	<0.1	>	0	0.2	0.2
Ascidiacea %	<0.1	>	0	0.2	0.2

3.4 Discussion

3.4.1 Factors influencing biodiversity

The addition of drill-cored artificial rock pools increased the number of species living on the mid-shore breakwater units studied. The pools were utilised by many species that were absent on the adjacent emergent rock surfaces. Further, they supported a much larger species pool than the emergent surfaces over time, and a comparable number of species to natural rock pools on nearby rocky shores. They were also just as productive as natural rock pools, even though the communities recorded in them were different, largely on account of differences in sessile assemblages (i.e. algae and encrusting fauna).

Low biodiversity on coastal defences has been attributed to a paucity of lower-shore and other desiccation-sensitive taxa, proportionally-rarer taxa and mobile fauna (Chapman 2003, Moschella et al. 2005, Pister 2009, Firth et al. 2015b). The artificial rock pools in this study appear to address each of these diversity deficits to some extent. Firstly, with regard to lower-shore taxa, some of the species recorded in the artificial pools (but not on the surrounding rock surfaces) were known to be present at lower-shore heights at the base of the breakwater units, where some moisture is retained at low tide (e.g. some members of the hydroids, ascidians and anemones; *pers. obs.*). It therefore appears that the artificial pools functioned similarly to rock pools in natural habitats (Metaxas and Scheibling 1993), by enabling extension of the vertical distribution of lower-shore species to mid-shore level on the structure. This may increase the capacity of the breakwater to support viable populations of these taxa, since the steep profile and high disturbance regime characteristic around the base of coastal defences (Moschella et al. 2005) may limit the extent of available habitat and reduce survivorship at low shore heights. Secondly, with regard to proportionally-rarer taxa, many of the species recorded in the artificial pools (but not on the surrounding rock surfaces) were present in much lower abundances overall (e.g. sponges, bryozoans and some algae) than the species that were common to both habitats (e.g. barnacles, gastropods and mussels). However, many of the proportionally-rarer species recorded in natural rock pools in the surrounding area were absent from the artificial pools. Thirdly, with regard to mobile fauna, the artificial pools supported several species of mobile fauna that were not otherwise living on the emergent rock surfaces (e.g. shannies, polychaete worms, chitons and anemones). Furthermore, the mobile species assemblages in the artificial pools were equivalent to those found in natural rock pools throughout most of the study. The same was not true, however, for the sessile assemblages (i.e. sessile fauna and algae), which were consistently significantly different in artificial and natural pools.

In general, the artificial rock pools supported more opportunistic algae (*Ulva intestinalis*) and sessile animals (*Sabellaria alveolata*, *Mytilus edulis* and *Spirobranchus* spp.) than natural rock pools, but coralline algae (encrusting Lithothamnia and erect *Corallina officinalis*) were notably absent (although a small crust of Lithothamnia was recorded in one artificial pool during the final survey in October 2014). Since the mobile faunal assemblages were the same in both habitats throughout most of the study, it is unlikely that herbivory (e.g. Lubchenco 1982, O'Connor and Crowe 2008; but see Noël et al. 2009a) or predation (e.g. Johnson et al. 1998, Silva et al. 2008) were dominant factors controlling sessile assemblage development. Instead, it is likely that physical and larval/propagule supply differences between the breakwater and natural rocky shore environments were more influential. In terms of physical differences, the artificial rock pools were cored into granite rock, thus they had vertical sides and their surfaces lacked the complexity and roughness of local natural intertidal rock (mixed sandstones and mudstones). Further, they were built into a breakwater of limited extent, surrounded by sandy sediment, which meant they were subject to increased scouring and were further from natural rocky shore source populations. This added distance from source populations may have led to differences in the larval and propagule supply to the breakwater compared to the natural shores, reducing the potential pool of colonisers. Although the breakwater supported many common rocky shore organisms, several taxa were absent (e.g. several algal species and some gastropods); the nearest source populations for those missing taxa were at a distance of >1000 m, compared to <10 m on natural shores.

Surface inclination has been shown to influence benthic community development previously (Connell 1999, Knott et al. 2004, Chapman and Underwood 2011). Therefore, the vertical sides of the artificial pools may have contributed to differences between artificial and natural rock pool communities. Firth et al. (2014a), however, found that substratum incline had little influence on rock pool epibiota, apart from in deeper (>20 cm) habitats. Opportunistic ephemeral algae, such as *Ulva* spp., can be reliably predicted to colonise bare substrata (Sousa 1979), but may be outcompeted by perennial species in more benign environments (Martins et al. 2007). This may explain the higher abundances of *U. intestinalis* in the more-disturbed artificial pools, and higher abundances of perennial corallines in the natural pools. Encrusting algae and some turf species are, however, considered reasonably stress-tolerant (Steneck and Dethier 1994), and although the smooth surface texture of the artificial rock pools may not have been optimal for propagule settlement, *C. officinalis* is capable of colonising smooth surfaces (Harlin and Lindbergh 1977) and is ubiquitous on granite and artificial boulder shores elsewhere (e.g. Pister 2009). Lithothamnia was recorded in one of the artificial pools at the end of the experiment, indicating that it, too, is capable of colonising smooth granite surfaces. It is likely, therefore, that the absence of coralline algae in the artificial pools throughout most of the study was due to limited dispersal capability (Dethier et al. 2003), since it was absent from the surrounding breakwater units. Conversely, for *S. alveolata*, *M. edulis* and *Spirobranchus* spp., source populations were locally-available at all sites. Therefore, although known gregarious settlers (Wilson 1968, Seed 1969, Klockner 1976), distance to source population was not a limiting factor for these species in the natural pools (where they were present in lower abundances). It is possible that the tube-building polychaete, *S. alveolata*, was more abundant in the artificial pools because of favourable hydrodynamics and a plentiful supply of suspended sand particles from the surrounding habitat (Wilson 1968). For the keel worms, *Spirobranchus* spp., it is possible that the granite surfaces of the artificial pools were favourable for settlement, since they are known to preferentially colonise smoother substrata (e.g. Barnes and Powell 1950, Andersson et al. 2009). With regard to *M. edulis*, however, it is probable that unexplained natural variability in larval supply led to higher abundances in the artificial pools, since they were all colonised simultaneously during one substantial settlement event at Tywyn in July 2012, shortly after the original artificial pools were installed. The distribution of *M. edulis* on open coasts has historically been considered erratic and unpredictable (Seed 1969); there is therefore little reason to expect that the same settlement and succession would occur in artificial pools installed at a different location or at a different time (discussed further below).

Coralline algae, *U. intestinalis*, *S. alveolata* and *M. edulis* can all be dominant space-occupiers (Suchanek 1978, Sousa 1979, Cunningham et al. 1984, Connell and Glasby 1999), and are important ecosystem engineers, encouraging (Barnes and Gonor 1973, Morse and Morse 1984) or inhibiting (Sousa 1979, Alestra et al. 2014) settlement, and providing habitat for other organisms (Seed 1996, Kelaher et al. 2001, Dubois and Retie 2002). It is therefore likely that the different relative abundances of these taxa (even if differences were only marked at certain stages of succession, as was true for *M. edulis* and *U. intestinalis*) had consequential implications for overall community development in artificial and natural rock pools, leading to the significant differences observed. The high photosynthetic rate of *U. intestinalis* (Larsson et al. 1997) may further have been responsible for the comparable levels of primary productivity in artificial and natural pools, despite the artificial pools supporting lower abundances of algae overall.

The lack of significant differences in mean primary productivity and species richness between artificial and natural rock pools may have been largely because of the relatively low GPP and richness recorded at one of the natural shore sites, Clarach (Figures 3.8 and 3.9). The observed locational variability between natural shore sites is an important factor in evaluating the potential for artificial rock pools to provide surrogate habitat for rocky shore biodiversity. The artificial pools may have supported lower richness than natural pools at Borth and Aberystwyth, and lower productivity than natural pools at Borth. Nevertheless, both richness and GPP in the artificial pools were likely to be within the range of what may be expected across natural rock pool habitats in general.

It is generally accepted that shallower rock pools experience more extreme environmental conditions than deeper pools (Metaxas and Scheibling 1993, Chan 2000, Firth and Williams 2009), and they also tend to support lower diversity and primary productivity (Martins et al. 2007, but see Firth et al. 2014a). Although in natural systems, both 12 cm and 5 cm deep rock pools would be considered relatively shallow (Firth et al. 2014a), the vertical sides of the cylindrical artificial pools trialled in this study may create more distinction in the habitats they provide. The shallower (5 cm) artificial pools did experience slightly greater fluctuations in temperature and pH (but not salinity) than the deeper (12 cm) pools (Appendix V), but they also appeared to allow more penetration of light to the bottoms and sides of the pools (*pers. obs.*). The deeper pools, although perhaps more stable in terms of water chemistry, frequently retained more coarse sediments (Appendix V), potentially causing greater physical disturbance from scouring. We found no significant difference between the 12 cm and the 5 cm artificial pools in terms of species richness or primary productivity, but their community structures were significantly different towards the end of the experiment. Deep artificial pools supported higher abundances of red and brown algae (*Polysiphonia* sp. and *Spongonema* sp.), whereas shallow artificial pools supported higher abundances of green algae (*U. intestinalis* and *Cladophora* sp.), which may have been limited by reduced irradiance in the deeper pools (Dring 1981). This apparent difference in light penetration may also explain the higher abundances of negatively phototactic *Spirobranchus* spp. (Klockner 1976) in the deeper pools. Deep pools, however, appeared to be *less* favourable for colonisation of *S. alveolata* and *M. edulis* (along with several proportionally-rarer species, including the polychaete *Lanice conchilega*), which were more abundant in the shallow pools, perhaps because of physical disturbances from scouring (Shanks and Wright 1986, Van Tamelen 1996). Frequent retention of sand in the shallow pools, in contrast, would have been beneficial for tube-building by *S. alveolata* (Wilson 1968) and *L. conchilega* (Feral 1989). Differences in abundances of the more cosmopolitan and stress-tolerant species (e.g. *A. equina*: Griffiths 1977, *P. vulgata*: Branch 1981, *L. pholis*: Davenport and Woolmington 2009) were apparent, although the causes remain unknown. Since the deep artificial rock pool communities were no more or less similar to natural rock pools than the shallow ones were, there is no reason to suggest that one design was more favourable for biodiversity than the other. Instead, it appears that the combination of 12 cm and 5 cm habitats resulted in greater Beta-diversity (among pools) than if they had all been of the same depth.

The timing of installation proved important in the early stages of artificial rock pool colonisation. Many more species settle out of the plankton between spring and autumn than during the winter months (e.g. see summary of records in Crisp and Southward 1958). Therefore, it was not surprising that delayed species accumulation was observed in artificial pools installed in autumn, but this response was much more pronounced in the artificial habitats than in natural pools whose colonisation started at the same time. In the latter stages of succession, however, the season in which artificial pools had been installed no longer predicated their species richness, although differences in community structure between spring- and autumn-installed pools remained throughout the study. Likewise, there were differences in community structure between spring 2012- and spring 2013-installed artificial pools, despite their colonisation following very similar trajectories otherwise. These community differences were likely to be the result of natural seasonal (e.g. Crisp and Southward 1958) and annual (e.g. Underwood and Fairweather 1989) variability (respectively) in larval and propagule supply, potentially driven by the substantial settlement of *M. edulis* that occurred in July 2012, before the autumn 2012- or the spring 2013-installed pools had been drilled. Since the spring 2102-installed artificial rock pool communities were no more or less similar to natural rock pools than the autumn 2012-installed ones were, there was no apparent biodiversity benefit of installing the pools at a particular time of year. Further, although the spring 2013-installed artificial pools were more similar to natural rock pools than the spring 2012-installed pools were (this was likely to be because of their different stages of succession, rather than a legitimate treatment effect), it appears reasonable to assume that the ecological outcomes of installing artificial rock pools would be similar from year to year.

3.4.2 Conclusions and management implications

There is increasing policy-maker recognition of the need to incorporate ecologically-sensitive design into marine and coastal developments (HM Government 2011, USACE 2012). In response, we trialled drill-cored artificial rock pools as a habitat enhancement intervention on an intertidal coastal defence breakwater. The desirability of different ecological responses to interventions will depend on specific secondary management objectives. Colonisation by species of conservation (e.g. *Sabellaria alveolata*) or commercial (e.g. *Mytilus edulis*) value (as was observed in this study; see also Bacchiocchi and Airoldi 2003, Airoldi et al. 2005b, People 2006, Devescovi and Iveša 2008, Firth et al. 2015a) may be positive for developments that seek to provide secondary socio-economic benefits or mitigate losses of natural habitats elsewhere. Similarly, colonisation by non-natives (e.g. *Austrominius modestus*, also observed in this study; see also Bulleri and Airoldi 2005, Vaselli et al. 2008, Airoldi and Bulleri 2011, Airoldi et al. 2015) may raise concern over the potential for interventions to facilitate the spread of invasive species. In the context of this study, the colonisation of *A. modestus* in the artificial rock pools was not of particular concern, since it was already present on the breakwater, and has become ubiquitous (even described as 'naturalised' by Tøttrup et al. 2010) on both artificial and natural substrata across Europe (e.g. Crisp 1958, Flowerdew 1984, Allen et al. 2006, Gomes-Filho et al. 2010, Bracewell et al. 2012, Gallagher et al. 2015). Nevertheless, it is important to consider the potential for enhancement interventions to promote colonisation by opportunistic species that take advantage of the unexploited bare substrata, in the same way that maintenance activities and other physical disturbances can (Airoldi et al. 2005b, Airoldi and Bulleri 2011).

In the absence of a single clear management objective from authorities (Moschella et al. 2005, Chapman and Underwood 2011, Firth et al. 2013a), in this study we were interested in whether the artificial rock pools would increase diversity on the breakwater and support natural rock pool community structure and function (i.e. primary production). We found, over 30 months of monitoring: (i) the artificial rock pools supported greater species richness than adjacent rock surfaces on the breakwater; (ii) the depth of artificial rock pools did not affect productivity or species richness, but 12 cm artificial pools supported different community structure to 5 cm artificial pools; (iii) the artificial rock pools supported equivalent productivity and species richness, but different community structure to natural rock pools on nearby rocky shores; (iv) artificial rock pools installed in spring 2012 supported equivalent species richness but different community structure to those installed in autumn 2012, and both supported equally dissimilar communities to natural rock pools; and finally (v) artificial rock pools installed in spring 2012 supported equivalent species richness but different community structure to those installed in spring 2013, and the spring 2013-installed pools supported more similar communities to natural pools than the spring 2012-installed pools (although this was likely to have been a product of their different stages of succession).

The artificial rock pools provided important habitat for several taxa that were otherwise absent at mid-shore height on the breakwater, particularly mobile animals, lower-shore taxa and some proportionally-rarer taxa, that have all been noted as absent from coastal defences in previous studies (Chapman 2003, Moschella et al. 2005, Pister 2009). While the artificial pools could not yet be considered fully functionally-equivalent to natural rock pools, successional trajectories suggest that climax communities had not yet been reached; artificial and natural rock pool community structure may yet converge over time. Continued monitoring will reveal whether, in particular, the recent settlement of Lithothamnia in one of the artificial pools will persist, and whether additional recruitment will occur, leading to communities more representative of natural pools.

In conclusion, these drill-cored artificial pools are an affordable, robust and effective means of enhancing biodiversity, and can be easily replicated in a variety of structures, both at the design stage and retrospectively. On the basis of our findings, reasonable advice to practitioners would be that Beta diversity may be increased by installing artificial pools with a variety of different depths (see also Firth et al. 2014a). Further, that installing artificial pools in spring and autumn (in any given year) will lead to similar ecological outcomes, although temporal variability in larval and propagule recruitment may result in different communities. Monitoring programmes for evaluating the success of interventions should be designed with this seasonal variability in mind, i.e. anticipating delayed colonisation during winter months, and subsequent fluctuations in diversity and community structure at different times of year. Monitoring protocols should also recognise the value of multivariate community-level assessment of ecological enhancement, demonstrated here as allowing much more thorough evaluation of outcomes than univariate diversity indices. More comprehensive policy guidance for ecological enhancement interventions may generate preferences for deeper or shallower pools, or for carrying out the enhancement at a particular time of year, e.g. to promote or discourage colonisation of certain species. Indeed, clarification of management objectives is greatly needed in order to develop the suite of effective ecological engineering techniques necessary to address the range of biodiversity deficits recorded in artificial habitats that are rapidly replacing natural coastlines globally.

CHAPTER FOUR

The desirability of potential secondary benefits of multi-functional coastal defence structures and steps to their effective implementation

Abstract

In order to fulfil international marine conservation commitments, governments have begun to recognise the need for more proactive marine planning policies and legislation, advocating sensitive engineering design that can deliver secondary benefits above and beyond the primary purpose of developments. In response, there is growing scientific interest in novel multi-functional coastal defence structures that can deliver secondary ecological and/or socio-economic benefits, thus supporting drivers for sustainable development. To ensure research efforts and resources are invested effectively, it is first necessary to determine what secondary benefits can potentially be built-in to engineered coastal defence structures, and further, which of these benefits would be most desirable. It is unlikely that secondary benefits will be perceived in the same way across different stakeholder groups (e.g. conservation groups, engineers, statutory bodies and researchers). Further, their order of priority when evaluating different design options is unlikely to be consistent, since each option will likely present a suite of compromises and trade-offs. The aim of this study was to investigate stakeholder attitudes towards multi-functional coastal defence developments across different sector groups. We carried out a perception study in England and Wales using two different survey techniques: a traditional quantitative questionnaire method and a semi-quantitative Delphi method. It was clear that stakeholders from different sectors had disparate personal and professional opinions on how coastal defence developments should be delivered. Our questionnaire survey, however, indicated unanimous support for implementing multi-functional coastal defence structures in place of traditional single-purpose ones. Our Delphi survey revealed a more nuanced and caveated level of support, but further elicited some general consensus that the most desirable secondary benefits that could be built-in to developments would be ecological ones (prioritised over social, economic and technical benefits). The panel also provided valuable information regarding perceived barriers and the necessary steps to widescale and effective implementation of multi-functional coastal defence developments. The Delphi method was found to be an effective means of synthesising information and expert judgements on complex problems that are not easily addressed using conventional survey techniques.

4.1 Introduction

Natural coastlines around the world are being replaced and reinforced by hard engineered structures such as seawalls, breakwaters and groynes (hereafter 'coastal defences'; e.g. Koike 1996, Davis et al. 2002, Chapman and Bulleri 2003, Airoldi and Beck 2007). The negative environmental impacts of these structures have been reasonably well-studied. In addition to direct loss and disturbance of species and habitats (Martin et al. 2005, Dugan et al. 2008), coastal defences can degrade natural landscapes (Burcharth et al. 2007), facilitate the spread of non-native species (Ruiz et al. 2009, Mineur et al. 2012, Airoldi et al. 2015), and alter coastal processes, having unintended knock-on effects elsewhere (Burcharth et al. 2007, Govaerts and Lauwaert 2009). Further, these artificial structures tend to be poor-quality habitats, supporting depauperate (Chapman 2003, Moschella et al. 2005, Firth et al. 2013b, 2015b) and ‘non-natural’ (Chapman and Bulleri 2003, Moschella et al. 2005) assemblages of marine life. Soft engineering approaches such as beach replenishment, sand dune stabilisation and managed realignment are widely considered to be more sustainable options for flood and erosion risk management (Capobianco and Stive 2000, Turner et al. 2007, Govaerts and Lauwaert 2009, Temmerman et al. 2013, Hanley et al. 2014). However, in scenarios where no alternative options are viable for protecting people and assets, shoreline management plans continue to recommend a strategy of ‘hold the line’ (Environment Agency 2009). This means that local authorities will be required to maintain existing defences and potentially implement additional ‘hard’ protection measures.

In order to fulfil international marine conservation commitments (e.g. those laid out in the OSPAR Convention and the Convention on Biological Diversity; also see Naylor et al. 2012 for an outline of relevant European and UK legal instruments), governments have begun to recognise the need for more proactive marine planning policies and legislation. For example, the UK’s Marine Policy Statement (HM Government 2011) advises that in addition to avoiding harm to marine ecology and biodiversity (§2.6.1.3), developments also “*may provide, where appropriate, opportunities for building-in beneficial features*” (§2.6.1.4). Although not prescribing a definitive obligation, this clearly advocates sensitive engineering design that can deliver secondary benefits above and beyond the primary purpose of developments (i.e. in the context of this research: coastal protection). In response, there is growing scientific interest in novel multi-functional coastal defence structures that can deliver secondary ecological and/or socio-economic benefits, thus supporting drivers for sustainable development (Challinor and Hall 2008; see also Zanuttigh et al. 2015).

There are few examples of truly and purposefully-designed multi-functional coastal defences around the world (but see Mead and Black 1999, Harris 2003, Jackson et al. 2012, Mendonça et al. 2012, Perkol-Finkel and Sella 2015, Scyphers et al. 2015). Single-purpose artificial reefs have been implemented to provide habitat for commercial fish species (Santos and Monteiro 1997, Spanier et al. 2010), to enhance marine biodiversity (e.g. Ambrose 1994, Allemand et al. 2000), and to provide amenity functions such as surfing (e.g. Fletcher et al. 2011), diving (e.g. Wilhelmsson et al. 2013) and sea angling (e.g. Wilson 1991). Their success, however, has been variable (see Baine 2001 for review of performance indicators). There are many similarities between artificial structures designed for habitat and amenity, and those designed for coastal defence, suggesting that multi-functional coastal defence structures should be viable (Challinor and Hall 2008). Indeed several of these habitat and amenity services have been reported to arise incidentally as secondary functions from traditional coastal defence structures (e.g. Collins et al. 1994, Pister 2009). But it has been argued that, unless designed with specific objectives in mind (e.g. target species), net ecological benefits are unlikely to be truly realised (Pickering and Whitmarsh 1997, Challinor and Hall 2008), and recreational uses are unlikely to be compatible (e.g. Airoldi et al. 2005b). Nevertheless, artificial surfing reefs are increasingly being adopted for coastal protection (Lokesha et al. 2013) and there is an expanding body of evidence to support the potential for ecologically-beneficial designs to be incorporated into coastal defence structures (e.g. Moschella et al. 2005, Chapman and Blockley 2009, Firth et al. 2013a, 2014b, Browne and Chapman 2014, Evans et al. 2015, Perkol-Finkel and Sella 2015).

Despite this known potential and policy recommendation, there remain numerous barriers to implementation of multi-functional coastal defence developments, perhaps as a function of the wider issue of ineffectual science-policy linkages (McNie 2007, Holmes and Clark 2008, Weichselgartner and Kasperson 2010). Further research is necessary to expand our knowledge base of alternative options, clarify choices and ultimately enable policy-makers to achieve desired outcomes (McNie 2007). But to ensure research efforts and resources are invested effectively, it is first necessary to determine what secondary benefits can potentially be built-in to engineered coastal defence structures, and further, which of these benefits would be most desirable. It is unlikely that secondary benefits will be perceived in the same way across different stakeholder groups (e.g. conservation groups, engineers, statutory bodies and researchers; Naylor et al. 2012; see also Zanuttigh et al. 2015). Further, their order of priority when evaluating different design options is unlikely to be consistent, since each option will likely present a suite of compromises and trade-offs. For example, the addition of pits, crevices and rock pools to artificial structures may be an effective way of increasing biodiversity (Chapman and Blockley 2009, Firth et al. 2014b, Browne and Chapman 2014, Evans et al. 2015) and stocks of exploited species (Martins et al. 2010), but they may not support the same assemblages of marine life as they do in natural systems (Evans et al. 2015; see also Chapter 3 of this thesis). Similarly, pre-cast concrete habitat enhancement units can be cheaply and easily deployed into structures (e.g. see BIOBLOCK demonstration project in Firth et al. 2014b), but the net ecological benefits of enhancement using concrete, with its associated large carbon footprint (Flower and Sanjayan 2007), may be questionable. Species of conservation interest can be transplanted onto structures (Clark and Edwards 1994, Perkol-Finkel et al. 2012), but this may have implications for local authorities tasked with maintaining those structures (Airoldi and Bulleri 2011). And reefs that aggregate commercial fish species may economically benefit professional and/or recreational fisheries (Collins et al. 1994), but they may lead to expedited over-exploitation if structures attract individuals from surrounding natural habitats rather than produce additional biomass (Pickering and Whitmarsh 1997). Habitat interventions may be designed with specific ecological and socio-economic responses in mind, but planners are required to judge the relative merits of each response in order to select the optimal design.

The aim of this study was to investigate stakeholder attitudes towards multi-functional coastal defence developments across different sectors groups. We carried out a perception study in England and Wales using two different survey techniques: a traditional quantitative questionnaire method and a semi-quantitative Delphi method (Dalkey 1969). We targeted stakeholders in England and Wales, specifically, because of the scale of the challenges regarding coastal flooding and erosion (i.e. almost 40% of the coastline of England and Wales is already under some form of coastal protection: Masselink and Russell 2013). The questionnaire was designed to gather broad exploratory information about perceptions of coastal defences and the potential to incorporate secondary benefits into developments. The Delphi method was then employed to elicit detailed information and professional judgements from a panel of experts and practitioners from seven different sectors. Our objectives were to: (i) determine the most important considerations for planning coastal defence developments (and their perceived order of priority); (ii) determine the potential secondary benefits that can be built-in to coastal defence developments (and their perceived order of priority); (iii) determine the level of support for implementing multi-functional coastal defences; and (iv) identify differences and consensus in perceptions across different sector groups. In light of comments received in the early stages of the Delphi study, we added a fifth opportunistic objective to: (v) identify the current barriers to effective implementation and steps for moving forward. Here we synthesise our findings and propose a four-step process to implementation of multi-functional coastal defence developments that can deliver secondary ecological and/or socio-economic benefits, as recommended by our environmental legislation.

4.2 Materials and Methods

4.2.1 Questionnaire survey

4.2.1.1 Survey instrument

A questionnaire was developed to gather quantitative data about perceptions of coastal defences and their potential to deliver secondary benefits (Appendix VII). Questionnaires were distributed (targeted and opportunistically) to stakeholders and members of the public in England and Wales between March 2013 and December 2014. Responses were received from 118 respondents and were assigned *post hoc* to eight different sector groups (Table 4.1). Members of the Public and Local Authority representatives were primarily from coastal areas, and Academic Non-specialists were primarily scientists. This was on account of the nature of the locations and events at which responses were opportunistically collected.

Table 4.1 Questionnaire survey: number of respondents from each sector.

*Statutory Bodies – Coastal Management and Nature Conservation

Sector	Number of respondents
Academic Non-specialist (ANS)	20
Academic Specialist (AS)	5
Conservation (C)	14
Ecological Consultant (EcC)	15
Engineering Consultant (EnC)	6
Local Authority (LA)	5
Statutory Bodies* (SB)	16
Public / Unknown (P)	37
N	**118**

Respondents were provided with some brief background information and were informed of the study objectives. Nine questions were asked to determine broad perceptions of coastal defences: their purpose, potential positive and negative impacts on the natural environment and society, the most important considerations when planning coastal defence developments, and the level of support for implementing different types of multi-functional engineering designs. Respondents were asked to select answers from lists of pre-defined options, in some cases indicating their order of importance on a numerical ranked scale between one and five (1 = ‘Most important’, 5 = ‘Least important’). Respondents were also asked to indicate their level of support for the concept of multi-functional structures on a ten-point forced-choice (i.e. no neutral option) visual Likert scale (Allen and Seaman 2007), between ‘Not supportive at all’ and ‘Very supportive’.

Responses were anonymised and coded to appropriate sector groups for analysis (Table 4.1).

4.2.1.2 Data analysis

Questions that required respondents to select one or more options from pre-defined lists were analysed as binary data (1 = selected, 0 = not selected) and the frequency of selection (% of respondents) was calculated for each option. For questions that required respondents to rank five options on a scale of importance (1 = ‘Most important’, 5 = ‘Least important’), individual ranks were converted to scores on an inverted scale (1 = low, 5 = high). Scores were summed over all responses, and also over responses provided by each of the eight sector groups separately. Total scores were then converted back into overall priority rankings between one and the number of options available for ranking n (1 = ‘High priority’, n = ‘Low priority’). One-way permutational analysis of variance (PERMANOVA; PERMANOVA+; Anderson 2001) was applied to test for differences in multivariate choices and rankings between sector groups. Analyses were based on Bray-Curtis similarity matrices of untransformed data, using 9999 unrestricted permutations.

Visual Likert scale responses were converted to scores between one and ten (1 = low, 10 = high), assuming even spacing between the ten-point scale intervals (Allen and Seaman 2007). A Wilcoxon Signed Ranks test was used to test for differences between overall median levels of support for traditional and multi-functional coastal defence structures. This non-parametric test was used because of non-normality in scores. One-way analysis of variance (ANOVA) and Kruskal-Wallis tests were used to test for differences in mean or median (respectively) levels of support between different sector groups, depending on whether the assumptions of approximate normality and homogeneous variances (confirmed using Levene’s test) were met.

Although ANOVA is considered reasonably robust against deviations from these assumptions (Underwood 1997), the unbalanced design of these analyses required a more conservative non-parametric approach. Student-Newman-Keuls post-hoc tests were used to identify pairwise significant differences. Univariate analyses were carried out in SPSS (IBM Corp. Version 21, 2012).

4.2.2 Delphi survey

4.2.2.1 Survey instrument

A Delphi survey was carried out between September and December 2014 to elicit more detailed information and expert judgements on the complex issues surrounding the subject of research. The method, originally developed in the 1950s in the field of military strategy (Dalkey and Helmer 1963), provides an interactive communication structure between the researchers and a panel of experts. Questions are asked over a number of rounds, and between each round, responses are analysed and fed back to the panel in an iterative process. This approach allows respondents to carefully consider and develop their answers over an extended period, in the context of rationale provided by other panel members (Garrod and Fyall 2000). Discrepancies and consensus may be identified (although consensus is not explicitly sought and will not be achieved if none exists), and information can be synthesised on highly complex and subjective problems that are not easily addressed using conventional questionnaires.

In this study the panel consisted of 16 experts and practitioners from seven different sector groups across England and Wales (Table 4.2). These sector groups were defined based on the responses received during the questionnaire survey (see Section 4.2.1.1). To ensure the experience and perspectives of panel members were relevant to the subject of research, the Local Authority panellists were invited from coastal local authorities and the Statutory Bodies panellists were from teams with a marine/coastal remit. Similarly, panel members from the Conservation, Ecological and Engineering Consultant sectors all had experience in marine and coastal issues, and the Academic Non-specialists were both marine scientists. Academic Non-specialists were included in the study since they were anticipated to contribute an objective, critical and scientifically-literate perspective to the discussion.

Table 4.2 Delphi survey: number of panel members from each sector.

*Statutory Bodies – Coastal Management and Nature Conservation

Sector	Number of respondents
Academic Non-specialist (ANS)	2
Academic Specialist (AS)	1
Conservation (C)	2
Ecological Consultant (EcC)	2
Engineering Consultant (EnC)	2
Local Authority (LA)	2
Statutory Bodies* (SB)	5
N	**16**

The size of the panel is not a critical feature of the Delphi technique (Smith 1995), but 'balance' in the panel, in terms of interests and expertise, is important (Wheeller et al. 1990). There is an accepted element of judgement regarding what constitutes a balanced panel (Wheeller et al. 1990); in this study we included a higher number of panel members from the Statutory Bodies sector due to the diversity of organisations and remits within that sector, and the applied nature of the issues being addressed.

The panel was first provided with a letter of participation (Appendix VIII), containing background information about the research and the study objectives. Panel members were asked to commit to three survey rounds: one scoping round and two convergence rounds (Green et al. 1990, Miller 2001), to be conducted over a period of three months. The scoping round consisted of three open-ended questions designed to gather full and detailed information on the subject of research (Box 1) (Appendix IX). Subsequent convergence rounds then asked the panel to rank n options under each of these three broad questions on a priority scale between one and n (1 = 'High priority', n = 'Low priority') and to indicate their level of agreement with constructed summary statements (Seely et al. 1980), either by selecting the statement they agreed with most or by indicating level of agreement on a standard five-point Likert scale (1 = 'Strongly disagree', 2 = 'Disagree', 3 = 'Neither agree nor disagree', 4 = 'Agree', 5 = 'Strongly agree') (Appendix IX). Between each round, responses were analysed and summarised in synthesis reports which were returned to the panel for consideration along with the next round of questions (Appendix X).

The study was conducted via email, retaining the panel's anonymity throughout. This avoided the risk of bias in responses caused by the influence of personality or institutional allegiances (Frechtling 1996). Panel members were asked to respond fully and thoughtfully and to provide rationale where appropriate. Responses were provided under the agreement that answers would not be considered representative of any organisation or sector, but that they would be reported as having been given by an expert/practitioner from the sector to which they had been assigned (Table 4.2).

Box 1. Three overarching questions answered by the Delphi survey panel

Q1. What are the most important considerations when planning coastal defence works (i.e. construction or maintenance of engineered coastal defence structures)?

Q2. What are the potential secondary benefits of engineered coastal defence structures (i.e. beyond their primary function of providing protection against flooding and erosion)?

Q3. Would you be more supportive of the construction of additional coastal defences around the UK if they were multi-functional structures (i.e. ones that deliver secondary ecological and/or socio-economic benefits)? Why?

4.2.2.2 Data analysis

Scoping round responses were coded using NVivo qualitative data analysis software (QSR International Pty Ltd. Version 10, 2014) and organised into overarching themes and subthemes for each question. Themes and subthemes were then translated into lists of options for ranking in subsequent rounds.

In convergence rounds, individual ranks assigned by panel members were converted to scores on an inverted scale between one and the number of options available for ranking n (1 = low, n = high). Scores were summed over responses from the whole panel, and also over responses provided by panel members from each of the seven sectors separately. Total scores were then converted back into overall priority rankings between one and *n* (1 = 'High priority', *n* = 'Low priority'). Box and whisker plots of median scores, interquartile ranges and outliers (i.e. ranks lying outside 1.5 times the interquartile range) were plotted in SPSS (IBM Corp. Version 21, 2012) to assess the level of consensus among the panel.

4.2.2.3 Progression through preliminary rounds

To place the Delphi study findings in context, and for transparency, it is appropriate to comment on how the process developed through preliminary rounds. Full question documents and synthesis reports for the three survey rounds are included in Appendices VIII and IX, respectively. We received 100% response rate in all three rounds of the survey.

In Round 1 (scoping round) responses, several main themes emerged, which were further organised into numerous subthemes. For Questions 1 and 2 (see Box 1), this information was synthesised into two lists of 20 considerations that were perceived important when planning coastal defence works, and 20 potential secondary benefits of engineered structures (respectively). For Question 3 (see Box 1), the information was used to construct six summary statements to reflect the range of opinions expressed, along with alternative opinions created for the purpose of the study. In Round 2 the panel was asked to rank the two lists in order of priority, and to indicate with which of the six statements they agreed most. Panel members were also asked to provide rationale for their responses, indicate their level of confidence in assigned ranks, and to provide any additional comments about the lists and statements presented.

Several panel members commented on the difficulty of ranking a list of 20 options on one linear scale of priority. It was apparent that some of the considerations presented in Question 1 were perceived as essential requirements (e.g. 'Fit for purpose') or higher-level considerations (e.g. 'Multi-functionality') that could not be meaningfully ranked alongside specific implementation-level considerations (e.g. 'Positive ecological impacts as a result of novel habitat'). Similarly, some of the potential secondary benefits presented in Question 2 were disputed, being perceived as essential requirements (e.g. 'Compensatory habitat creation'), higher-level considerations (e.g. ‘Foster community support’) or primary benefits (e.g. ‘Positive ecological impacts as a result of defence function’), rather than true secondary benefits. Based on comments received, for Question 1 we reduced the initial list of 20 considerations down to a new list of ten implementation-level considerations to take forward to Round 3. In the reduced list, essential considerations were combined, higher-level considerations were removed or modified, and associated positive and negative impacts were combined into *net* impacts. Elements having inherent value beyond their importance to local communities and businesses (e.g. landscape, education and outreach, etc.) were, however, not included in the combined ‘Net socio-economic impacts’ option. To account for this forfeit of detail regarding the relative importance of associated positive and negative impacts, we constructed a summary statement (Box 2) with which panel members were asked to indicate their level of agreement. For Question 2, we split the initial list of 20 potential secondary benefits into two new lists of 15 implementation-level secondary benefits (i.e. features that could actively be built-in to hard coastal defence structures) and ten potential reasons for building them in, to take forward to Round 3.

In response to various concerns raised in previous rounds, in Round 3 the panel were explicitly asked to consider potential secondary benefits “*as beneficial features of a hard defence structure evaluated against the same hard defence structure without the added beneficial features*” (i.e. not against alternative coastal management strategies). They were also asked to assume that “*the secondary benefits can be built-in to structures with no compromise of primary function or additional negative impacts, and that they can achieve their intended purpose*”.

In Round 1, the panel provided valuable comments regarding perceived barriers to effective implementation and suggestions for moving forward. Although the survey did not explicitly seek comment on these themes, we felt that this was valuable information and therefore included additional questions to gather more complete perceptions in subsequent rounds. Several additions were put forward in Round 2, from which two lists of ten current barriers and ten suggestions for moving forward were constructed to take forward to Round 3.

4.3 Results

Since the questionnaire survey was opportunistic in nature and did not achieve large or balanced sample sizes, only select results are included here to supplement the main findings from Round 3 of the Delphi survey. Full questionnaire survey results and findings from previous rounds of the Delphi survey are included in Appendices X and IX, respectively.

4.3.1 Broad perceptions of coastal defence structures (questionnaire responses only – please refer to Appendix XI for summary tables)

The majority of questionnaire respondents selected ‘Protect against flooding and erosion’ as the primary purpose of coastal defence structures (selected by 87.3% of respondents), whilst a small proportion selected ‘Stabilise the coastline’ (13.6%). The most frequently-selected secondary purposes were ‘Stabilise the coastline’ (69.5%), ‘Increase amenity value / access for recreation’ (39.0%) and ‘Provide hard substrate for marine life to colonise’ (28.0%). These perceptions were consistent across different sector groups (Pseudo-$F_{7,117}$ = 1.033, *P*(perm) = 0.418).

When asked about the potential benefits, negative impacts and most important considerations for planning coastal defences, however, there were significant differences in questionnaire responses from different sectors (Pseudo-$F_{7,117}$ = 1.420, *P*(perm) = 0.037). Engineering Consultant perceptions differed significantly to those of Academic Non-specialists (t = 1.844, *P*(perm) = 0.006), Conservationists (t = 1.56, *P*(perm) = 0.028), Ecological Consultants (t = 1.976, *P*(perm) = 0.001), the Public (t = 1.626, *P*(perm) = 0.012) and Statutory Bodies (t = 2.193, *P*(perm) = 0.001). Responses from the Statutory Bodies sector also differed to Local Authorities (t = 1.569, *P*(perm) = 0.030) and members of the Public (t = 1.460, *P*(perm) = 0.037). Overall, questionnaire respondents ranked ‘Provide hard substrate for marine life to colonise’, ‘Protect against flooding and erosion’ and ‘Stabilise the coastline’ as the most important potential benefits of coastal defence structures. Engineering Consultants, however, did *not* prioritise ‘Provide substrate for marine life’, instead favouring ‘Increase landscape value’. Overall, respondents ranked ‘Alter natural coastal processes’, ‘Degrade the natural environment’ and ‘Spoil the landscape’ as the most important negative impacts of coastal defence structures. Few respondents selected ‘They do not cause any negative impacts’ (2.5%), whilst a slightly higher proportion selected ‘Their importance for protecting the coast outweighs any negative impact’ (8.5%). One Engineering Consultant argued that

> “*The importance for protection should easily outweigh the negative impacts; otherwise we should question the need for the structure.*”
>
> (Engineering Consultant)

The most important considerations for planning coastal defence works were perceived by questionnaire respondents to be their ‘Defence function’, ‘Environmental impact’, ‘Longevity’, ‘Cost’ and ‘Visual impact’. These priorities echoed (but simplified) many of the opinions expressed by the Delphi panel when asked the same or similar questions (see below).

4.3.2 Most important considerations when planning coastal defence developments

In Round 3 Question 1 of the Delphi study, the panel were asked to rank a list of ten considerations for planning coastal defence works twice: firstly based on the *current* order of priority in practice (Table 4.3, ‘Panel[1]’), and secondly based on what they thought the order of priority *should* be (Table 4.3, ‘Panel[2]’). Panellists were given the option of not completing the ranking for the former (Panel[1]) if they felt unqualified to do so. Twelve panel members provided answers, four of whom indicated that they felt somewhat unqualified but had provided their “best informed guess”. The overall order of priority was the same regardless of whether these data were included or excluded. Unsurprisingly, the panel ranked ‘Essential criteria’ as the most important consideration. They then ranked ‘Cost’, ‘Net socio-economic impacts on local communities and businesses’ and ‘Net ecological impacts’, but indicated that ‘Net ecological impacts’ *should* be considered more important than ‘Net socio-economic impacts’, and both *should* be considered more important than ‘Cost’. At the other end of the scale, ‘Carbon footprint’, ‘Opportunities for research and development’ and ‘Opportunities for education and outreach’ were ranked as the lowest priorities currently, but the panel indicated that ‘Carbon footprint’ and ‘Opportunities for research and development’ *should* be given higher priority than ‘Level of community support’ and ‘Net culture and heritage impacts’.

There was a relatively high degree of consensus for the panel’s highest and lowest rankings of how considerations *should* be prioritised (Figure 4.1). However, there was very little consensus regarding the importance of ‘Cost’, ‘Landscape impacts’, ‘Carbon footprint’ and ‘Community support’. Panel members from the Conservation sector and the Statutory Bodies sector perceived ‘Cost’ to be less important than those from other sectors (Table 4.3); in fact, panel members from the Conservation sector collectively ranked it as their lowest priority. Views expressed on ‘Cost’ varied widely, for example:

> “*I believe all of the considerations listed … to be of greater importance than the overall cost of the coastal defence works.*”
>
> (Statutory Bodies)

> “*In an ideal world the cost of defence structures would not be as important as their primary functionality … and their net ecological impacts*.”
>
> (Academic Non-specialist)

> “*[Cost] is still sort of fixed and I’m not sure you can rank it.*”
>
> (Local Authority)

> “*We are in very challenging financial times and the drivers around any capital spend have to be set against this background.*”
>
> (Statutory Bodies)

Whilst ranking ‘Cost’ low, panel members from the Conservation and Statutory Bodies sectors ranked ‘Carbon footprint’ higher than the rest of the panel, and the Conservation sector also ranked ‘Opportunities for education and outreach’ (lowest priority overall) higher than the rest of the panel. It was suggested that

> “*We can only change perception of FCERM [Flood and Coastal Erosion Risk Management] if education is built in better to schemes.*”
>
> (Statutory Bodies)

Table 4.3 Considerations for planning coastal defence works in order of priority, as indicated by combined rankings of the Delphi panel (Panel[1] = perceived *current* order of priority, Panel[2] = *preferred* order of priority) and by combined rankings of panel members from different sectors (1 = high, 10 = low).

ANS: Academic Non-specialist; AS: Academic Specialist; C: Conservation; EcC: Ecological Consultant; EnC: Engineering Consultant; LA: Local Authority; SB: Statutory Bodies

CONSIDERATIONS	Panel[1]	Panel[2]	ANS	AS	C	EcC	EnC	LA	SB
Essential criteria (i.e. part of a sustainable strategy, justification, in line with environmental legislation and planning guidelines, public safety, fit-for-purpose, no unintentional alteration to coastal processes, affordable/funding available)	1	1	1	1	1=	1	1	1	1
Cost (i.e. assuming funding is available)	2	4	4	4	10	3	3=	2=	6
Net socio-economic impacts on local communities and businesses (i.e. assuming minimum requirements are met and not including risk reduction from primary defence function: e.g. reduced/enhanced amenity, recreation, fisheries, navigation, tourism, employment, etc.)	3	3	3	3	5	4	3=	2=	3
Net ecological impacts (i.e. assuming minimum requirements are met and not including risk reduction from primary defence function: e.g. loss/disturbance of habitats/species, dispersal of invasive non-native species, extraction of raw materials, novel habitat/refuge for exploited species or species of conservation interest, etc.)	4	2	2	2	1=	2	2	2=	2
Net landscape impacts (i.e. assuming minimum requirements are met)	5	5	5=	6	6=	5	5	5=	5
Level of community support (i.e. assuming minimum requirements are met)	6	8	7	5	6=	6=	6	7	9
Net culture and heritage impacts (i.e. assuming minimum requirements are met and not including risk reduction from primary defence function: e.g. loss/damage of heritage features or archaeology, platform for art installations, etc.)	7	9	9	7	6=	8	7=	5=	8
Carbon footprint (i.e. assuming minimum requirements are met: e.g. processing and transport of raw materials, construction emissions, etc.)	8	6	8	8	3	9	7=	9	4
Opportunities for research and development (e.g. new engineering designs, experimental units to investigate marine/coastal ecology)	9	7	5=	10	4	6=	7=	8	7
Opportunities for education and outreach (e.g. platform for environmental education, etc.)	10	10	10	9	6=	10	10	10	10

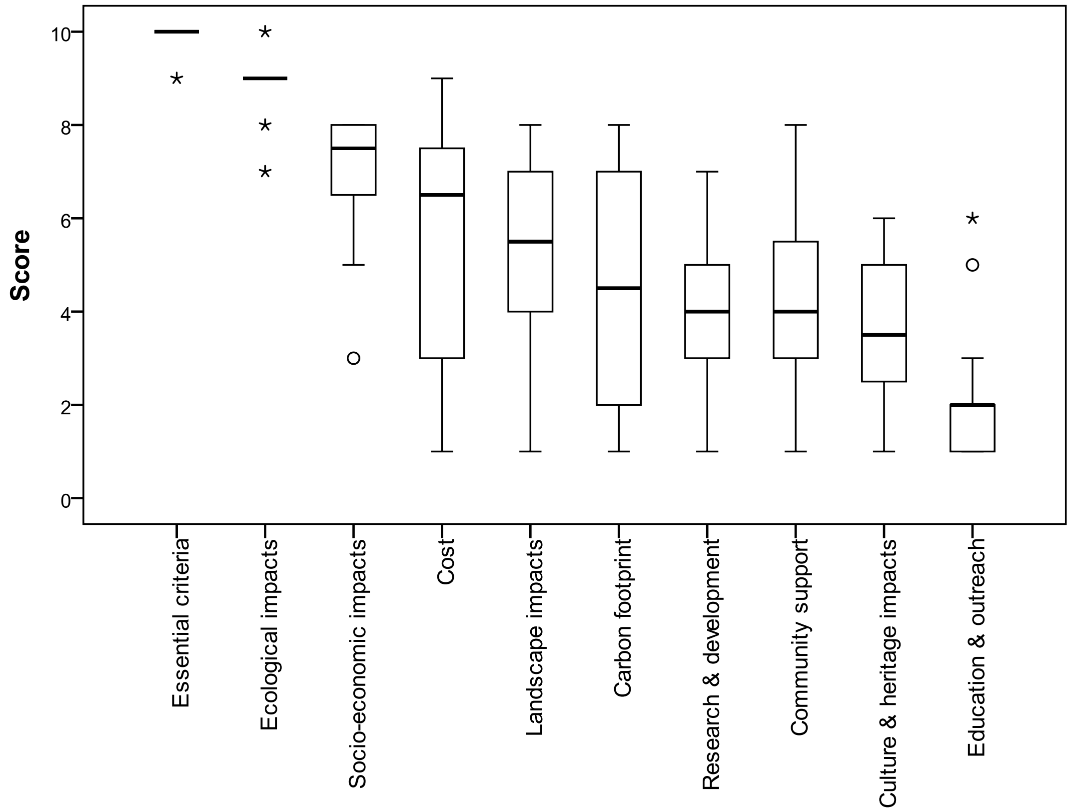

Figure 4.1 Median scores (inverted ranks in *preferred* order of priority, i.e. 10 = high, 1 = low) assigned to considerations for planning coastal defence works by the Delphi panel, with interquartile ranges (box), maximum/minimum scores (whiskers), outliers > 1.5 x interquartile range (circles) and extreme outliers > 3 x interquartile range (stars).

To investigate the relative importance of associated positive and negative impacts on ecology and local communities (in the context of planning coastal defence developments), we constructed a summary statement, with which panel members were asked to indicate their level of agreement (Box 2).

Box 2. Summary Statement 1

"Considerations for avoiding/minimising negative impacts are more important than considerations for creating/maximising positive impacts."

Fifteen (out of 16) panel members indicated that they ‘Agree’ or ‘Strongly Agree’ that considerations for avoiding/minimising negative impacts are more important than considerations for creating/maximising positive impacts. Some panel members raised concern, however, regarding the generality of the statement, e.g.

> “*Certainly for ecology and coastal processes – not sure if this necessarily applies to businesses.*”
>
> (Local Authority)

One panellist from the Statutory Bodies sector indicated that they ‘Strongly Disagree’ with the statement, commenting that

> “*Any new structure will have a negative impact, just avoiding/minimising is not really good enough, the aim should be to do something better.*”
>
> (Statutory Bodies)

4.3.3 Level of support for implementing multi-functional coastal defence structures

Questionnaire responses collectively indicated significantly increased levels of support for additional coastal defence structures in the UK *if they were multi-functional structures* (Wilcoxon Z = -7.377, $P < 0.001$) (Figure 4.2), and the magnitude of increase was consistent across all sectors ($F_{7,117} = 1.250$, $P = 0.282$). Respondents from the Statutory Bodies sector indicated the lowest mean levels of support for both standard (4.1 ± 0.6 SE) and multi-functional structures (5.8 ± 0.7 SE), whilst respondents from the Engineering Consultant sector indicated the highest levels of support (7.7 ± 0.8 SE and 9.0 ± 0.5 SE, respectively). The difference in support for additional (non multi-functional) coastal defence structures between these two sectors was significant ($F_{7,117} = 2.578$, $P = 0.017$; SNK $P < 0.05$).

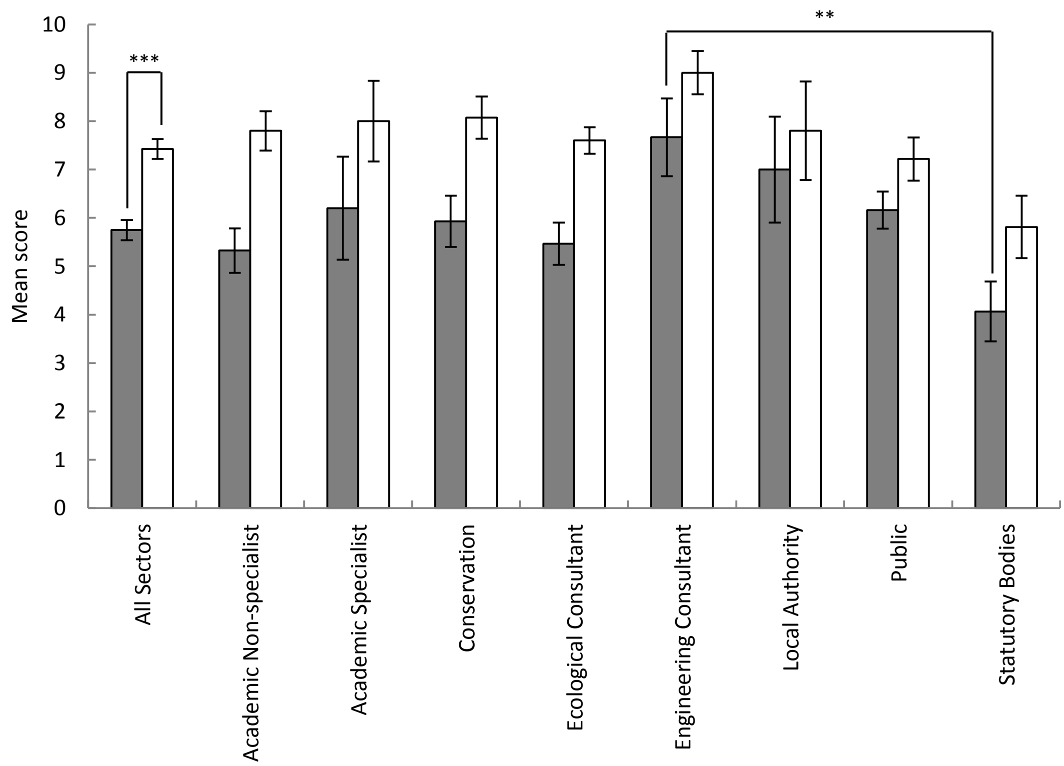

Figure 4.2 Level of support for additional coastal defence structures (grey bars) and additional multi-functional coastal defence structures (white bars), as indicated by mean scores (± SE; n = 118) assigned by questionnaire respondents on a scale of 1 to 10 (1 = 'Not supportive at all', 10 = 'Very supportive'). Significant differences are indicated (**: p < 0.05, ***: p < 0.001).

The Delphi panel also expressed support for the concept of multi-functional coastal defence developments. In Round 2 Question 3, the panel was asked to indicate with which of six summary statements they agreed most (Figure 4.3). Largely, opinion was divided between Statements 5 and 4, reflecting caveated support for multi-functional structures, and Statement 2, reflecting more general support for multi-functional structures *if* new structures are deemed necessary. One panel member from the Statutory Bodies sector selected Statement 1, citing concerns about unsustainable long-term coastal management. In contrast, several panel members expressed disagreement with this statement (and with Statements 6 and 2), suggesting that in certain scenarios hard defences are necessary and part of the strategic approach to Flood and Coastal Erosion Risk Management (FCERM). Several panel members indicated that their opinions would be better-represented by a combination of two or more statements. In particular, Statement 4 was frequently referred to as a second choice by those who selected Statement 5, and vice versa.

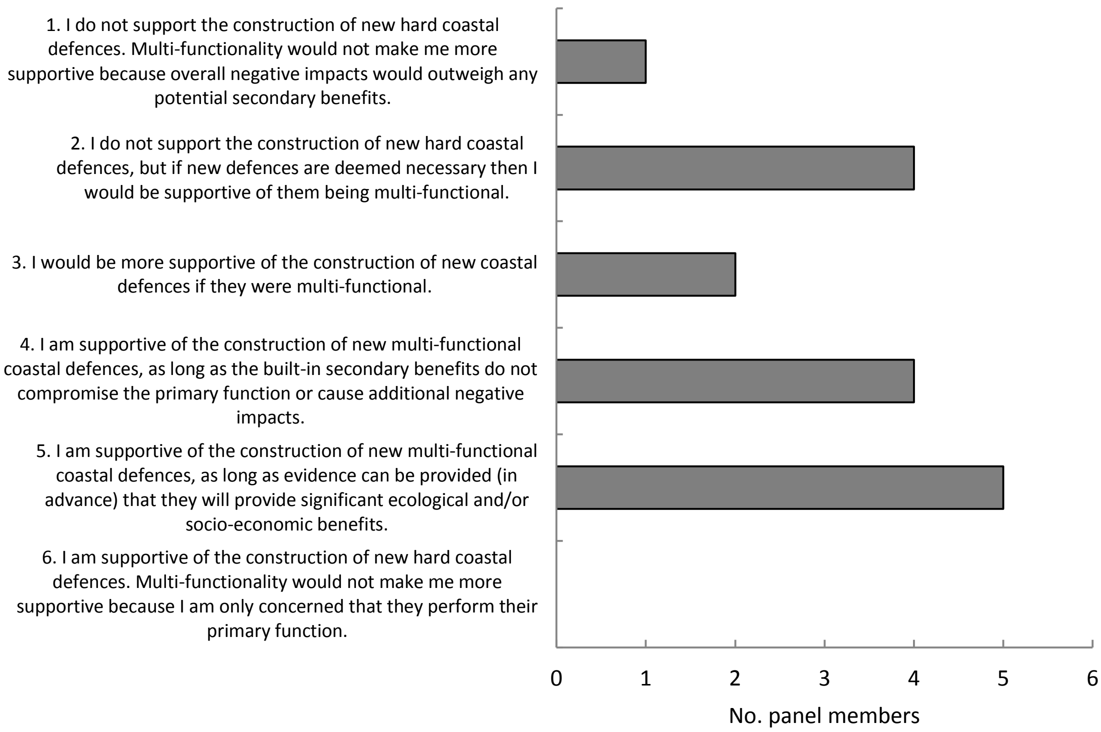

Figure 4.3 Frequency of selection for each of six summary statements by the Delphi panel. Panel members were asked to select the statement with which they agreed most.

Moving forward to Round 3 we constructed a new summary statement which combined elements of the most favoured statements from Round 2, and did not include any reference to support or non-support of hard coastal defences in general (Box 3). Fifteen (out of 16) panel members indicated that they 'Agree' or 'Strongly Agree' that they would be more supportive of hard coastal defence structures (where deemed necessary) being multi-functional structures, as long as the two caveats in Summary Statement 2 (Box 3) were satisfied.

Box 3. Summary Statement 2

"Where hard coastal defence structures are deemed necessary, I would be more supportive of them being multi-functional structures, as long as built-in secondary benefits do not compromise primary defence function or cause additional negative impacts, and evidence can be provided that intended ecological and/or socio-economic benefits will be realised."

One panel member from the Engineering Consultant sector selected 'Neither Agree nor Disagree', commenting that

> "*It is important to demonstrate that there is a benefit from an engineering perspective too, some positive feedback that makes the structure perform better.*"
>
> (Engineering Consultant)

Two panel members also felt that the statement should specify that

> "*The secondary benefits should be of a reasonable cost.*"
>
> (Local Authority)

and that any additional cost would need to be

> "*in proportion to the effect/evidence.*"
>
> (Statutory Bodies)

Conversely, three panellists (from the Conservation, Academic Non-specialist and Statutory Bodies sectors) felt that the statement was too constrained by the need to provide evidence, which may be an unreasonable obstacle to implementation. It was suggested that

> "*There will always be a level of uncertainty … [but] this should not be a reason NOT to design structures with secondary aims in mind.*"
>
> (Academic Non-Specialist)

Instead, based on existing evidence from other areas,

> "*There should be a presumption that there will be some positive effect.*"
>
> (Statutory Bodies)

4.3.4 Potential secondary benefits that can be built-in to coastal defence structures (and motivations for building them in)

Overall questionnaire rankings (Appendix XI) indicated most support for multi-functional coastal defence structures that 'Increase habitat complexity', 'Support species of conservation value', 'Support natural rocky shore communities', 'Can be used for research or education purposes' and 'Support commercially valuable species'. The most frequently-selected reasons for being more supportive of multi-functional structures were 'Might as well get the most out of new developments' (selected by 59.3% of respondents), 'This would reduce the impact on the environment' (55.1%) and 'This would enhance the environment' (53.4%). The most frequently-selected reason for being less supportive was 'This would be more expensive' (15.3%). Perceptions were consistent across sectors (Support for different types of structures: Pseudo-$F_{7,110}$ = 0.656, P(perm) = 0.910; Reasons for support: Pseudo-$F_{7,113}$ = 1.310, P(perm) = 0.155).

In Round 3 Question 2 of the Delphi study, the panel ranked 'Habitat for natural rocky shore communities', 'Habitat for species of conservation interest' and 'Refuge for exploited species' as the highest priority secondary benefits that could be built-in to multi-functional coastal defence structures (Table 4.4, 'Panel'). At the other end of the scale, the panel perceived 'Opportunities for education and outreach', 'Enhanced landscape value' and 'Enhanced culture and heritage value' as the lowest priorities. Accordingly, the panel indicated that ‘Positive ecological impacts’, ‘Divert pressure from natural systems’ and ‘Positive socio-economic impacts on local communities and businesses’ were the primary motivations for implementing multi-functional designs in coastal defence developments. ‘Culture and heritage’, ‘Education and outreach’ and ‘Reduce carbon footprint’ were of least concern (Table 4.5, ‘Panel’).

There was a reasonable level of consensus in the panel’s highest and lowest ranked secondary benefits (Figure 4.4a) and reasons for building them into developments (Figure 4.4b). However, there was little agreement regarding the middle ranks. With regard to secondary benefits (Table 4.4), the Academic Specialist assigned their top ranks differently to the rest of the panel, prioritising socio-economic and technical benefits (i.e. ‘Enhanced amenity/recreation’, ‘House other technologies’ and ‘Enhanced commercial fisheries’) above the more direct ecological benefits. They commented that

> “*When it comes to building in actual benefits, the socio[-economic] ones are of higher priority, partly because the ecological ones can be built in around [them]*.”
>
> (Academic Specialist)

Panel members from the Local Authority and Engineering Consultant sectors also ranked ‘Enhanced amenity/recreation’ high, whereas those from the Conservation and Statutory Bodies sectors ranked this particularly low. Panel members from the Conservation sector instead favoured ‘Safeguarded biosecurity’, as did the Academic Specialist and Ecological Consultants, whereas the Engineering Consultants ranked this as their lowest priority. The Engineering Consultants also ranked ‘Refuge for exploited species’ lower than the rest of the panel, but instead prioritised ‘Reduced carbon footprint’ and ‘Enhanced landscape value’. Finally, panel members from the Academic Non-specialist and Statutory Bodies sectors ranked ‘Mariculture opportunities’ higher than the panel as a whole. Some considered this as an opportunity for co-location of marine activities, akin to ‘House other technologies’, and ranked it high

> “*given the increasingly busy state of the seas*.”
>
> (Statutory Bodies)

However, others were sceptical of the viability of this secondary benefit

> "*due to differences in the scale of the operation and the optimal location for such activities.*"
>
> (Academic Non-Specialist)

and raised concern about

> "*introductions of species novel to the system.*"
>
> (Ecological Consultant)

This latter concern was shared by several panel members in relation to some of the highest ranking ecological benefits, i.e. 'Habitat for natural rocky shore communities', 'Habitat for species of conservation interest' and 'Habitat heterogeneity in structure design'. The importance of site-specific decision-making was a clear message from the panel throughout the process, i.e. any potential ecological benefits must be evaluated in the context of local natural habitats.

When ranking reasons for building-in benefits (Table 4.5), panel members from the Engineering Consultant and Local Authority sectors assigned their highest priority differently to the rest of the panel, i.e. 'Reduce maintenance requirements' and 'Increase likelihood of scheme progression', respectively. However, panellists from both sectors ranked 'Positive ecological impacts' and 'Positive socio-economic impacts' joint second, indicating agreement with the overall panel perception that these are primary motivations for building-in secondary benefits. In contrast, panel members from the Conservation and Ecological Consultant sectors assigned particularly low priority to 'Increase likelihood of scheme progression'. One panel member commented that

> "*If a defence structure is being planned it is a necessity in whatever form decided upon … therefore, I believe it is not a case that it will progress any faster/smoother as a result of added enhancements.*"
>
> (Ecological Consultant)

Panellists from the Conservation sector also ranked 'Positive socio-economic impacts' much lower than the rest of the panel. Instead they prioritised 'Reduce carbon footprint', 'Research and development' and 'Education and Outreach'. Academic Non-specialists and Ecological Consultants also ranked 'Research and development' higher than the rest of the panel, whereas the Academic Specialist again ranked this low. There was little agreement in ranks assigned to 'Enhance/safeguard landscape': although panel members from the Academic Non-specialist, Ecological Consultant and Statutory Bodies sectors ranked it fairly high, it was lowest priority for the Academic Specialist as they felt

"*It is not really a secondary benefit.*"

(Academic Specialist)

Also at the bottom of the rankings, 'Culture and heritage' and 'Education and outreach' were consistently perceived as low priority considerations for secondary benefits. Rationale for this was provided by some panel members, including that there are more appropriate places to cater for these activities, and also that it is difficult to value them and identify a beneficiary through which to balance associated costs.

Table 4.4 Potential secondary benefits that can be built-in to multi-functional coastal defence structures in order of priority, as indicated by combined rankings of the Delphi panel and by combined rankings of panel members from different sectors (1 = high, 15 = low).

ANS: Academic Non-specialist; AS: Academic Specialist; C: Conservation; EcC: Ecological Consultant; EnC: Engineering Consultant; LA: Local Authority; SB: Statutory Bodies

SECONDARY BENEFITS	Panel	ANS	AS	C	EcC	EnC	LA	SB
Habitat for natural rocky shore communities (e.g. build-in microhabitat complexity and use materials suitable for natural rocky shore communities)	1	2	9	4	1	1=	5	1
Habitat for species of conservation interest (e.g. build-in habitat suitable for wintering birds, BAP species, etc.)	2	4=	5	1=	5	1=	2	3
Refuge for exploited species (e.g. build-in refuge habitat suitable for exploited species to allow populations to persist)	3	4=	7	1=	2=	9=	6	2
Habitat heterogeneity in structure design (e.g. build-in mosaic of habitats such as rocky substrate, sediments, saltmarsh patches, etc.)	4	1	6	5	2=	4	3=	5
Enhanced commercial fisheries (e.g. build-in refuge/nursery habitat for commercial species)	5	3	3	7	6=	5=	3=	8
Safeguarded biosecurity (e.g. build-in features to remove/reduce competitive advantage of non-native invasive species)	6	8=	4	3	4	15	7	7
Enhanced amenity/recreation (e.g. build-in surf reef design, promenade, beach access, recreational fishing platform, etc.)	7=	10	1	13	8=	3	1	12
House other technologies (e.g. build-in turbines, masts, etc.)	7=	11	2	8=	6=	9=	8	6
Mariculture opportunities (e.g. build-in facilities for mussel/macroalgae culture)	9	4=	8	10	13	13=	9	4
Reduced carbon footprint (e.g. use novel low-carbon materials or recycled waste materials)	10	12	11	8=	11=	5=	14	9
Opportunities for research and development – new engineering solutions (e.g. trial novel materials and structural designs)	11	7	10	11=	11=	8	10	13=
Opportunities for research and development – investigating marine/coastal ecology (e.g. build-in experimental mesocosm units)	12	8=	14	6	10	11	11=	13=
Enhanced landscape value (e.g. use natural materials, subtle design or aesthetically-attractive design)	13	13	15	14	8=	5=	11=	10
Opportunities for education and outreach (e.g. build-in facilities for public engagement or environmental education)	14	14=	13	11=	14	13=	15	11
Enhanced culture and heritage value (e.g. build-in art installations)	15	14=	12	15	15	12	13	15

Table 4.5 Potential reasons for building-in secondary benefits to coastal defence structures in order of priority, as indicated by combined rankings of the Delphi panel and by combined rankings of panel members from different sectors (1 = high, 10 = low).

ANS: Academic Non-specialist; AS: Academic Specialist; C: Conservation; EcC: Ecological Consultant; EnC: Engineering Consultant; LA: Local Authority; SB: Statutory Bodies

REASONS FOR BUILDING-IN SECONDARY BENEFITS	Panel	ANS	AS	C	EcC	EnC	LA	SB
Positive ecological impacts (i.e. through enhanced connectivity/resilience of rocky habitats, habitat for exploited species, habitat for species of conservation concern, habitat heterogeneity, etc.)	1	1	3	1	1	2=	2=	1
Divert pressure from natural systems (i.e. by providing access for recreation, fisheries, research, co-location with other technologies etc.)	2	2=	1	2=	2	5	4	4
Positive socio-economic impacts on local communities and businesses (i.e. through enhanced amenity, recreation, fisheries, navigation, tourism, employment, etc.)	3	2=	2	8	3	2=	2=	2=
Increase likelihood of scheme progression (i.e. by fostering public support and improving partnership funding potential)	4	4=	5	7	9	4	1	5
Reduce maintenance requirements (i.e. by building-in positive feedback in stability of structure)	5	7	4	6	6=	1	5	8
Research and development (i.e. gather evidence necessary for moving forward with multi-functional coastal defences by trialling novel engineering designs and improving knowledge of marine/coastal ecology)	6	4=	9	4	4	6=	6	6
Enhance/safeguard landscape (i.e. by using natural materials, subtle design or aesthetically-attractive design)	7	4=	10	9	5	6=	7=	2=
Reduce carbon footprint (i.e. by using low carbon technology, recycled materials, etc.)	8	9=	6	2=	6=	8	9	7
Education and outreach (i.e. by building-in facilities for public engagement and environmental education)	9	9=	8	5	8	10	10	9
Culture and heritage (i.e. by building-in art installations, etc.)	10	8	7	10	10	9	7=	10

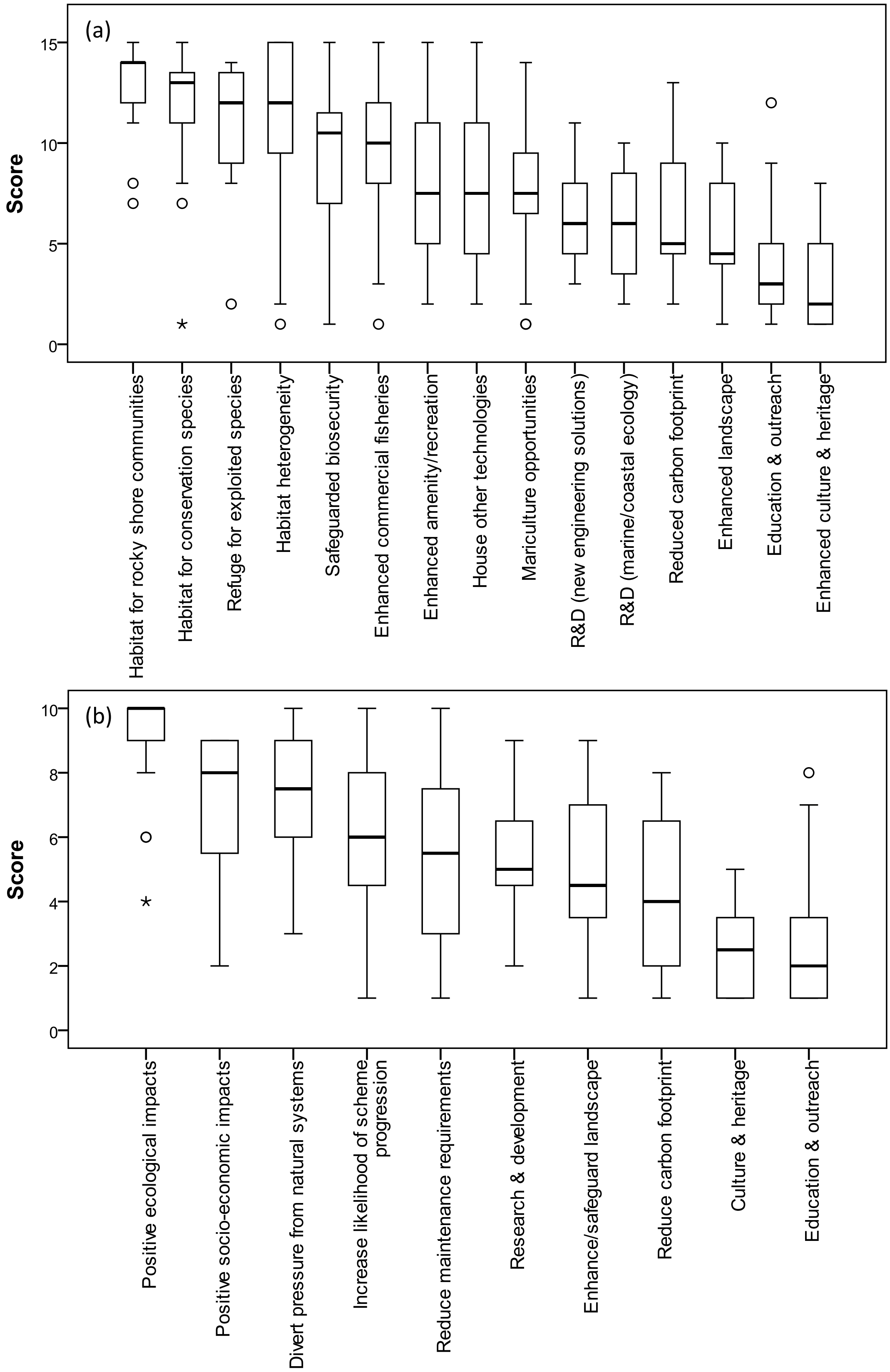

Figure 4.4 Median scores (inverted ranks, i.e. 15/10 = high, 1 = low) assigned to (a) potential secondary benefits and (b) reasons for building them into developments by the Delphi panel, with interquartile ranges (box), maximum/minimum scores (whiskers), outliers > 1.5 x interquartile range (circles) and extreme outliers > 3 x interquartile range (stars).

4.3.5 Current barriers to effective implementation of multi-functional coastal defences

In Round 3 Question 3 of the Delphi study, the panel was asked to rank ten current barriers to effective implementation of multi-functional coastal defence structures and ten suggestions for moving forward, in order of priority (Table 4.6). However, several panel members commented that all of the barriers and suggestions were pertinent, and little consensus was apparent in the rankings (Appendix X). Others commented on the logical order in which barriers and suggestions for moving forward should be addressed. We utilised these comments to propose a four-step process to effective implementation of multi-functional coastal defence developments (Box 4), which we discuss further below.

Table 4.6 Current barriers to implementation and suggestions for moving forward with multi-functional coastal defence structures in order of priority, as indicated by combined rankings of the Delphi panel (1 = high, 10 = low).

CURRENT BARRIERS TO EFFECTIVE IMPLEMENTATION	Panel
Developments driven by cost and funding priorities	1
Lack of policy drive and legislative support	2
Ability to justify additional costs	3
Reliable assessment of value	4
Awareness of / engagement with the concept of multi-functionality	5
Lack of evidence that benefits will be realised	6
Poor communication between sectors during planning	7
Lack of well-understood 'products' (i.e. ecological engineering solutions)	8
Lack of understanding of ecology of manmade habitats	9
Lack of collaboration with EU/international partners (i.e. knowledge exchange)	10
SUGGESTIONS FOR MOVING FORWARD	**Panel**
Consider multi-functional designs in the planning stage of new defences	1
Strengthen legislative framework	2
Conduct cost-benefit analyses of potential secondary benefits	3
Conduct experimental trials to gather additional evidence	4
Make additional resources available to cover cost of multi-functional features	5
Improve awareness and engagement amongst relevant sectors	6
Develop 'products' that can be incorporated into scheme designs	7=
Develop new technologies to improve potential of multi-functional structures	7=
Expand beneficiary pays principal to include secondary benefits	9
Collaborate with EU/international partners (knowledge exchange)	10

4.4 Discussion

4.4.1 General consensus in priorities for coastal defence developments

Effective flood and coastal erosion risk management (FCERM) demands negotiation of many complex and conflicting stakeholder priorities. It is clear that stakeholders from different sectors have disparate personal and professional opinions on how coastal defence developments should be delivered. Our questionnaire survey, however, indicated unanimous support for implementing multi-functional coastal defence structures in place of traditional single-purpose ones. Our Delphi survey revealed a more nuanced and caveated level of support, but further elicited some general consensus in terms of perceived highest and lowest priorities, despite the diverse panel composition with experts and practitioners from seven different sectors.

In general, the most important considerations for planning coastal defence developments (after ensuring essential criteria are met) were perceived to be their net ecological impacts and net socio-economic impacts on local communities and businesses. When asked about potential secondary benefits that could be built-in to developments, the Delphi panel favoured ecological benefits over social, economic and technical ones. Accordingly, primary motivations for incorporating secondary benefits were to deliver positive ecological and socio-economic impacts for the local environment and communities. However, there was general agreement that it is more important to avoid or minimise negative impacts of developments than it is to create and maximise positive ones.

All of the considerations and potential secondary benefits evaluated in the Delphi study were put forward as being important by the panel. As such, none were considered unimportant or irrelevant. However, in general, the lowest priority considerations for coastal defence developments (and the secondary benefits that can be built-in to them) were perceived to be the provision of opportunities for education and outreach, and the net cultural and heritage impacts. Although it is widely accepted that direct experiences in nature can promote more environmentally-conscious behaviour (e.g. Kals et al. 1999), it was suggested that there are more appropriate opportunities for engaging the public with the marine environment. However, as one panellist commented, better education and outreach may be necessary to generate community support for more sustainable long-term management strategies. Community involvement in strategic planning has become commonplace in recent years (Ledoux et al. 2005) and in some cases, uninformed citizen-based decisions have led to inappropriate management strategies (e.g. Young et al. 2014).

It was pointed out that the absence of representation from the education, culture and heritage sectors on the panel may have biased the overall rankings against these options. This should be acknowledged as a limitation of the study. The panel was constructed so as to balance inclusion of a wide range of sectors with the practicalities of processing responses within a reasonable time frame, and the likelihood of retaining 100% participation throughout the study.

4.4.2 Proposed steps to implementation of multi-functional coastal defences

As policy and legislation begins to recognise the need for developers to take a more pro-active role in protecting and enhancing the natural environment (e.g. HM Government 2011), our study provides some much-needed clarity on what can be done to deliver secondary ecological and socio-economic benefits from coastal defence developments. Based on findings from the Delphi study, we propose a logical four-step approach to wide-scale and effective implementation of multi-functional coastal defence developments (Box 4), which will be useful to inform the future direction of research in this field. Although we present a four-step process, it is important to note that we are not starting from the beginning of *Step 1* (i.e. gathering evidence). A wealth of general evidence already exists globally to support methods of enhancing artificial structures for environmental, social and economic benefit (e.g. see reviews by Baine 2001, Moschella et al. 2005, Chapman and Underwood 2011, Firth et al. 2014b). Nevertheless, a lack of evidence that secondary benefits can be realised, and a lack of understanding of the ecology of artificial habitats, were both perceived as barriers to effective implementation by the Delphi panel. This led to the general consensus that they would be more supportive of multi-functional coastal defence structures *only if evidence can be provided* that the intended benefits will be realised (Box 3). It was pointed out by some that this obligation to provide evidence may become an unreasonable obstacle to implementation. The Academic Specialist commented that

> “*Thankfully we are now sitting on a wealth of proof-of-concept studies and word is getting out [but] the field is so much in its infancy that we need to … communicate the possibilities before we can … get the opportunities to do more testing.*”
>
> (Academic Specialist)

This echoes previous appeals in literature (Bulleri and Chapman 2010, Chapman and Underwood 2011, Naylor et al. 2012), i.e. implementation (with experimental control and long-term monitoring) is necessary in order to gather further evidence.

Box 4. Steps to effective implementation of multi-functional coastal defences

Step 1: Gather evidence of efficacy of secondary benefits

Conduct a systematic evidence-gathering exercise, firstly collating existing evidence from the literature and via knowledge exchange with international partners, and secondly filling any knowledge gaps through experimental trials.

Step 2: Value secondary benefits

Conduct cost-benefit analyses to make reliable valuations of the net benefits of different engineering options. It may be possible to identify beneficiaries of potential secondary benefits to attract additional partnership funding.

Step 3: Develop new technologies and ecological engineering “products”

Expand existing knowledge of ecological engineering solutions, from high-level design concepts and materials, to off-the-shelf habitat enhancement units tailored to support specific target species and services.

Step 4: Encourage implementation

Facilitate knowledge exchange and uptake to improve awareness and engagement amongst relevant sectors, and to encourage communication about multi-functional options during the planning stage of new developments.

Another key barrier to implementation (as perceived by the Delphi panel) was the ability to justify additional costs that may be associated with multi-functionality. Throughout the study, there was considerable discrepancy in opinions regarding the importance of cost. Although financial constraints are often a substantive limitation of conservation efforts globally (e.g. McKinney 2002, Balmford et al. 2003, McCarthy et al. 2012), there is increasing recognition of the value of goods and services that can be supported by a healthy natural environment (Costanza et al. 2014). Numerous tools are available for assessing the value of these goods and services (e.g. Mitchell and Carson 1989, Hanley et al. 1998, Carr and Mendelsohn 2003) and the associated costs of protecting them (e.g. MARXAN, Ball et al. 2009). But although socio-economic secondary benefits of coastal defence developments may be readily evaluated (e.g. enhanced commercial fishery), further research is necessary (*Step 2*) to reliably assess the non-use value of (and justify additional costs of) potential *ecological* secondary benefits (e.g. provision of habitat for conservation species). The panel acknowledged the challenging financial climate in which FCERM decisions are necessarily being made in the UK (Committee on Climate Change 2014) (as in other parts of the world), but also pointed out the potential to attract partnership funding (Defra 2011) from identified beneficiaries of potential secondary benefits. Again, potential sources of partnership funding may be more obvious for socio-economic secondary benefits than for ecological ones, but it was suggested that the beneficiary could conceivably be

> "*UK PLC*"
>
> (Statutory Bodies)

if none more specific could be identified (i.e. benefits to society in general could attract public funding; see Seattle Seawalls case study described in Naylor et al. 2012 for an example of this).

As stressed by the Delphi panel and many of the questionnaire respondents, any built-in secondary benefits must be designed (and evaluated) in the context of the local environment and communities in question. They must also be tailored to the requirements of the specific targeted species or services desired. Through further experimental trials, new technologies and products may be developed (*Step 3*) to provide a catalogue of off-the-shelf ecological engineering solutions necessary to deliver the range of potential secondary benefits that have been identified (see *Future directions for research* in Bulleri and Chapman 2010). Since so many coastlines have already been artificially hardened globally (e.g. Koike 1996, Davis et al. 2002, Chapman and Bulleri 2003, Airoldi and Beck 2007), it is important to seek engineering solutions that can be applied retrospectively to existing structures (e.g. Martins et al. 2010, Firth et al. 2014b, Browne and Chapman 2014, Evans et al. 2015, Perkol-Finkel and Sella 2015) as well as to investigate multi-functional designs for new developments (e.g. Chapman and Blockley 2009, Jackson et al. 2012, Firth et al. 2014b, Perkol-Finkel and Sella 2015, Scyphers et al. 2015).

Some Delphi panel members commented that the legislative framework, communication between sectors and awareness of multi-functional structures all exist, despite them being perceived as barriers by others. They instead suggested that what is lacking is the robust evidence needed to drive policy changes and encourage engagement with the concept of multi-functionality. In reality, the greater barrier appears to be a lack of awareness of, or access to, the body of evidence that currently exists. It is unrealistic to expect practitioners across different sectors to keep abreast of the rapidly-expanding body of academic literature in this field (Holmes and Clark 2008). Instead, it may be necessary for researchers to pro-actively facilitate knowledge exchange and uptake through training sessions and practitioner-focused workshops (e.g. URBANE Project Final Stakeholder Workshop, 2013 www.urbaneproject.org/final-stakeholder-workshop; CIRIA CPD Course/Workshop 'Working with nature to enhance hard infrastructure assets' www.ciria.org/CIRIA/Navigation/Events/Event_Display.aspx?EventKey=E15208). The role of 'interpreters' (Holmes and Clark 2008), 'boundary organisations' (McNie 2007) or 'knowledge brokers' (Naylor et al. 2012) has been championed in the science-policy literature. These individuals or organisations 'bridge the gap' between the producers and users of knowledge, to ensure research is more visible and useful to decision-makers (McNie 2007, Holmes and Clark 2008, Naylor et al. 2012). The independent not-for-profit body, CIRIA (the Construction Industry Research and Information Association, www.ciria.org), has emerged as an effective intermediary group in the field of ecological engineering and green infrastructure in the UK (but also operating internationally). If *Steps 1-3* can be achieved, and evidence can be effectively communicated to policy-makers and practitioners, then more specific policies may develop to strengthen the legislative framework in which secondary benefits are considered. This would provide the incentive and confidence required to encourage engagement and communication between sectors about multi-functional options during the planning stage of new developments (*Step 4*).

4.4.3 The Delphi method as a tool for effective environmental management

In this study we applied the Delphi method to elicit and untangle stakeholder perceptions regarding: (i) the most important considerations for planning coastal defence developments; (ii) the potential secondary benefits that can be built-in to coastal defence structures; (iii) the level of support for multi-functional coastal structures; and (iv) the steps necessary to achieve their effective implementation. We were also able to identify consensus and conflicts between panel members from different sector groups. This is valuable information for informing marine and coastal planning decisions that seek to balance environmental, social and economic priorities. A defining principle for the effective conservation of wild living resources (Mangel et al. 1996) is that it takes account of the motives, interests and values of all users and stakeholders, *but not by simply averaging their positions*. We advocate the Delphi method as an effective means of synthesising information and expert judgements on complex problems that are not easily addressed using conventional survey techniques.

CHAPTER FIVE

General Discussion

5.1 Thesis overview and summary

Natural coastal habitats around the world are being replaced and modified by engineered structures (e.g. Koike 1996, Davis et al. 2002, Chapman and Bulleri 2003, Airoldi and Beck 2007). In light of predicted sea level rise and increasing storminess (Donat et al. 2011, Young et al. 2011, IPCC 2013), it is likely that artificial structures will continue to proliferate to protect expanding coastal developments (Koike 1996, Thompson et al. 2002, Govaerts and Lauwaert 2009). In response to evolving marine planning policies (e.g. HM Government 2011), it is becoming increasingly necessary to incorporate ecologically-sensitive design into coastal developments, not only to minimise their environmental impacts, but also to maximise potential ecological and socio-economic secondary benefits.

The concept of ecological engineering is not new (Schulze 1996, Bergen et al. 2001). In terrestrial and freshwater systems the potential for incorporating environmental enhancements into engineered developments has been well-studied. For example, green roofs (Brenneisen 2006, Hui and Chan 2011), motorway wildlife passages (Van Wieren and Worm 2001, Mata et al. 2008), coir rolls for riverbank stabilisation (Johnson et al. 2002, Hoggart and Francis 2014) and bird/mammal nest boxes (Arnett and Hayes 2000, Stamp et al. 2002) have all been widely implemented, allowing rigorous evaluation of their efficacy. There has also been a lot of research into the optimal design of culverts and dams for fish migration (e.g. Monk et al. 1989, Russon et al. 2010, Newbold et al. 2014). Consequently, the principles of ecological engineering and green infrastructure are embedded in urban planning practice for terrestrial and freshwater restoration or development projects (e.g. Brenneisen 2006, Williams 2010, Hale and Sadler 2012). In marine planning, however, ecological engineering remains an emerging concept. Much progress has been made in recent years in identifying potential interventions for enhancing biodiversity on artificial structures in the marine and coastal environment (e.g. Chapman and Blockley 2009, Langhamer and Wilhelmsson 2009, Chapman and Underwood 2011, Browne and Chapman 2014, Firth et al. 2014b, Perkol-Finkel and

Sella 2015), which typically provide poor-quality habitats for marine life (e.g. Chapman 2003, Moschella et al. 2005, Firth et al. 2013b, Aguilera et al. 2014). There remain, however, several knowledge gaps preventing progress towards multi-functional coastal defence developments that incorporate ecological secondary benefits. As a consequence, there are few examples of effective implementation globally (but see Harris 2003, Scyphers et al. 2015).

I investigated artificial coastal defence structures as surrogate habitats for rocky shore biodiversity, and the potential for the design of structures to be manipulated to achieve more beneficial outcomes from coastal defence developments. I focused on three major knowledge gaps that must be addressed in order to effectively incorporate ecologically-sensitive design into coastal defences: (i) the capacity to predict ecological responses to different engineering designs for coastal defence structures; (ii) the potential for ecological engineering interventions to enhance biodiversity on structures; and (iii) stakeholder perceptions regarding the desirability of potential secondary benefits that can be built-in to developments. In this concluding chapter, I briefly summarise the main findings of my research in the context of their application to marine planning and conservation management. I then highlight the knowledge gaps that remain and outline the necessary steps towards wide-scale and effective implementation of multifunctional coastal defence developments.

5.1.1 Coastal defence structures as habitats in Wales, UK

Artificial coastal structures have frequently been reported to support different, often less diverse and less ‘natural’, communities of marine life, compared with adjacent natural rocky shores (Chapman 2003, Chapman and Bulleri 2003, Pinn et al. 2005, Moschella et al. 2005, Pister 2009, Firth et al. 2013b, 2015b, Aguilera et al. 2014). I surveyed 125 intertidal coastal defence structures (including breakwaters, groynes, harbour walls, revetments, scour defence and seawalls) at 55 locations around the coast of Wales, UK. I recorded 113 different taxa colonising the structures, including numerous brown, red and green macroalgae, and many mobile and sessile fauna (Appendix III), in various different community groupings (Chapter 2). Several structures did support low biodiversity, particularly those confined to the upper part of the shore (e.g. seawalls and revetments). Others, however, supported very species-rich communities, particularly those that were positioned in (or extended into) the sublittoral fringe (e.g. harbour walls and long shore-perpendicular groynes). In contrast to the widely-reported phenomenon of artificial habitats supporting non-native and invasive species (e.g. Bulleri and Airoldi 2005, Tyrrell and Byers 2007, Vaselli et al. 2008, Dafforn et al. 2012, Airoldi et al. 2015; but see Pister 2009), I found few non-natives on the structures I surveyed around Wales. Exceptions were the acorn barnacle, *Austrominius modestus*, the green macroalga, *Codium fragile*, and the slipper limpet, *Crepidula fornicata*. *Austrominius modestus* was ubiquitous on over 80% of the structures surveyed and has become pervasive (described as a 'naturalised' component of intertidal communities: Tøttrup et al. 2010) in both natural and artificial habitats around Europe in recent decades (e.g. Crisp 1958, Flowerdew 1984, Allen et al. 2006, Gomes-Filho et al. 2010, Bracewell et al. 2012, Gallagher et al. 2015). *Codium fragile* and *Crepidula fornicata* were each recorded on only one structure (Aberystwyth harbour wall and Swansea scour defence, respectively), in both cases adjacent to marinas which are known to be particularly susceptible to invasion via vessel movements (Gollasch 2002, Floerl and Inglis 2003, Lambert and Lambert 2003, Glasby et al. 2007, Griffith et al. 2009, Dafforn et al. 2009, Rius et al. 2014, Airoldi et al. 2015). The reason for the observed absence of many non-native species on coastal defences around Wales is unclear; it may in part be on account of the remote rural nature of much of the coast, removed from major transport routes and with fairly low-intensity recreation. Other species of note colonising structures included the reef-building polychaete *Sabellaria alveolata* (of conservation interest in the UK: Frost 2004) and the edible mussel *Mytilus edulis* (of habitat and commercial value: Seed 1996). Both were recorded fairly frequently on structures, but often in low abundances. However, on structures positioned low in the intertidal zone, with high exposure to wave energy and a plentiful supply of suspended sand particles, these two species were characteristically-prominent components of the colonising communities (with 'Frequent' relative abundance scores on the SACFORN scale: Hiscock 1996).

5.1.2 Potential for ecologically-sensitive design of coastal defence structures

Community development in intertidal habitats is often determined by a number of interacting physical, environmental and biological factors (e.g. Foster 1971, Menge and Sutherland 1987, Mullineaux and Garland 1993, Johnson 1994, Green et al. 2012). If developers are to effectively evaluate different design options for coastal defence developments, it is necessary to improve our ability to predict the biological communities that will colonise different types of structures in different locations. In Chapter 2, I modelled the relationship between a number of physico-environmental parameters and the biological communities colonising different types of structures. I demonstrated that, given the nature of the shoreline on which a new coastal defence was required (i.e. the surrounding sediments and level of exposure to prevailing wind and waves), it would be possible to predict (with up to 62% confidence) the characteristic community that could be expected to colonise a structure, based on its broad shape, position in the intertidal zone, and abundance of microhabitats. This model is not a finished product (see suggestions for improvement in Chapter 2), yet it demonstrates the potential for this statistical approach, using empirical observations from existing developments, to inform marine planning decisions. It further highlights the value of post-construction monitoring of colonising communities (which is rarely implemented following coastal defence developments) for improving our understanding of the ecological implications of future developments (discussed previously by Airoldi et al. 2005a). There may further be application to other marine developments beyond coastal defences (e.g. marine renewables infrastructure and artificial reefs), and potentially also in freshwater (e.g. dams and bridge supports) and terrestrial environments (e.g. land proposed for re-wilding), although clearly with appropriate selection of applicable predictor variables in each case.

In Chapter 3, I explored the potential for ecological engineering interventions to enhance biodiversity on coastal defence structures. Since diversity deficits on intertidal structures have often been attributed to low topographic complexity (Chapman 2003, Moschella et al. 2005, Aguilera et al. 2014, Firth et al. 2015b), particularly a lack of water-retaining features (Chapman 2003, Aguilera et al. 2014, Firth et al. 2015b; see also Firth et al. 2013b), I trialled a novel design of drill-cored artificial rock pools on an intertidal riprap breakwater in Wales. Over a 30-month period, I found that the artificial pools performed an important ecological function on the structure. They were utilised by numerous species that were not otherwise recorded on surrounding emergent rock surfaces (Figure 5.1a, b), including taxa that have frequently been reported to be absent or scarce on coastal defences previously (e.g. mobile fauna, lower-shore taxa and proportionally-rarer taxa: Chapman 2003, Moschella et al. 2005, Pister 2009, Aguilera 2014). Furthermore, the artificial pools were just as productive as natural rock pools and supported a comparable number of species. The composition of communities in artificial and natural pools, however, was different, largely on account of differences in sessile assemblages (i.e. algae and encrusting fauna; Figure 5.1b, c). Therefore, although the artificial pools were clearly an effective means of increasing biodiversity on the breakwater, they could not be considered fully functionally-equivalent to natural rock pools (although community structure may yet become more similar to natural pools over time).

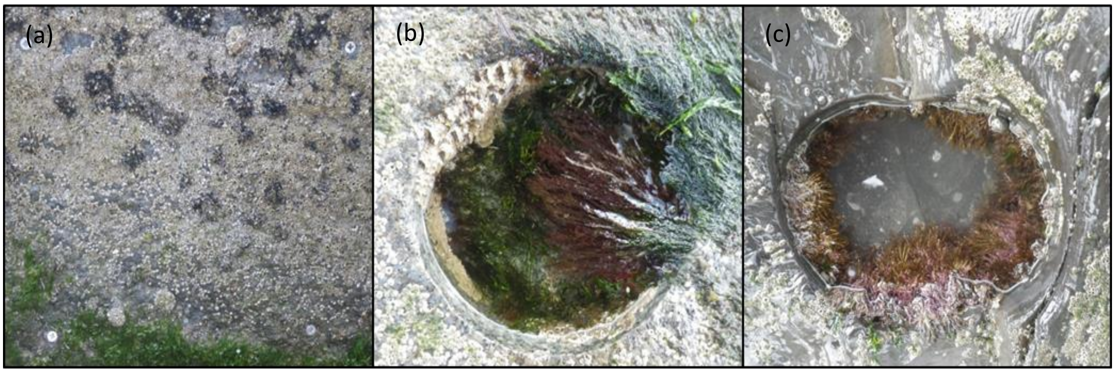

Figure 5.1 Examples of communities colonising each of three experimental habitats that were monitored over 30 months to assess the potential for drill-cored rock pools as a habitat enhancement intervention on an intertidal coastal defence breakwater: (a) emergent granite surface on the breakwater; (b) drill-cored artificial rock pool on the breakwater; (c) natural rock pool on a nearby natural rocky shore.

The cost of the intervention is directly related to the time taken to drill the artificial pools, which in turn is directly related to the depth of the pools created. I found that shallow (5 cm deep) artificial pools supported equivalent species richness and productivity to deeper (12 cm deep) artificial pools, but their community compositions differed. Similarly, pools drilled in spring and in autumn resulted in similar increases in diversity on the breakwater, but different communities developed in the two sets of pools on account of differences in initial recruitment and subsequent succession. More comprehensive policy guidance for ecological enhancement interventions may generate preferences for deeper or shallower pools, or for carrying out the enhancement at a particular time of year (e.g. to promote or discourage colonisation of certain species). Researchers have called for greater clarity in management objectives previously (Moschella et al. 2005, Chapman and Underwood 2011, Firth et al. 2013a; also discussed further below), yet Chapman and Underwood (2011) point out that each scenario is probably unique and requires specific consideration.

In light of the uncertainty regarding the *type* of colonising communities that would be considered desirable in response to different design options and/or enhancement interventions on coastal defence structures, I investigated stakeholder attitudes across different sector groups in England and Wales. Chapter 4 describes the findings from a quantitative questionnaire survey and a semi-quantitative Delphi survey (Dalkey 1969), involving stakeholders from eight different sector groups (i.e. academic specialists and non-specialists, ecological and engineering consultants, local authorities, statutory bodies, conservationists and members of the public). It was clear that stakeholders from different sectors had disparate personal and professional opinions on how coastal defence developments should be delivered. There was, however, unanimous support for implementing multi-functional coastal defence structures in place of traditional single-purpose ones (where hard defences were considered necessary in the first place), and in general the most desirable secondary benefits that might be built-in to coastal defences were ecological benefits (prioritised over social, economic and technical ones). Specifically, the Delphi panel indicated that provision of habitat for natural rocky shore communities, species of conservation interest, and commercially-exploited species (i.e. provision of refuge for population conservation, rather than for fisheries benefit) would be the most desirable ecological secondary benefits that could be built-in to coastal defences. There was also general consensus, however, that it is more important to avoid or minimise negative impacts of developments than it is to create and maximise positive ones. Echoing Bulleri and Chapman (2010), the panel further strongly believed that any built-in secondary benefits must be designed (and evaluated) in the context of the local environment and communities in question. They must also be tailored to the requirements of the specific targeted species or services desired (Challinor and Hall 2008).

5.2 Knowledge gaps and steps to effective implementation of multi-functional coastal defence developments

In Chapter 4, I proposed a logical step-wise approach to wide-scale and effective implementation of multi-functional coastal defence developments (Chapter 4, Box 4; also illustrated here: Figure 5.2). I reiterate this here, in the context of the wider outcomes of my research and with broader discussion of the knowledge gaps that remain.

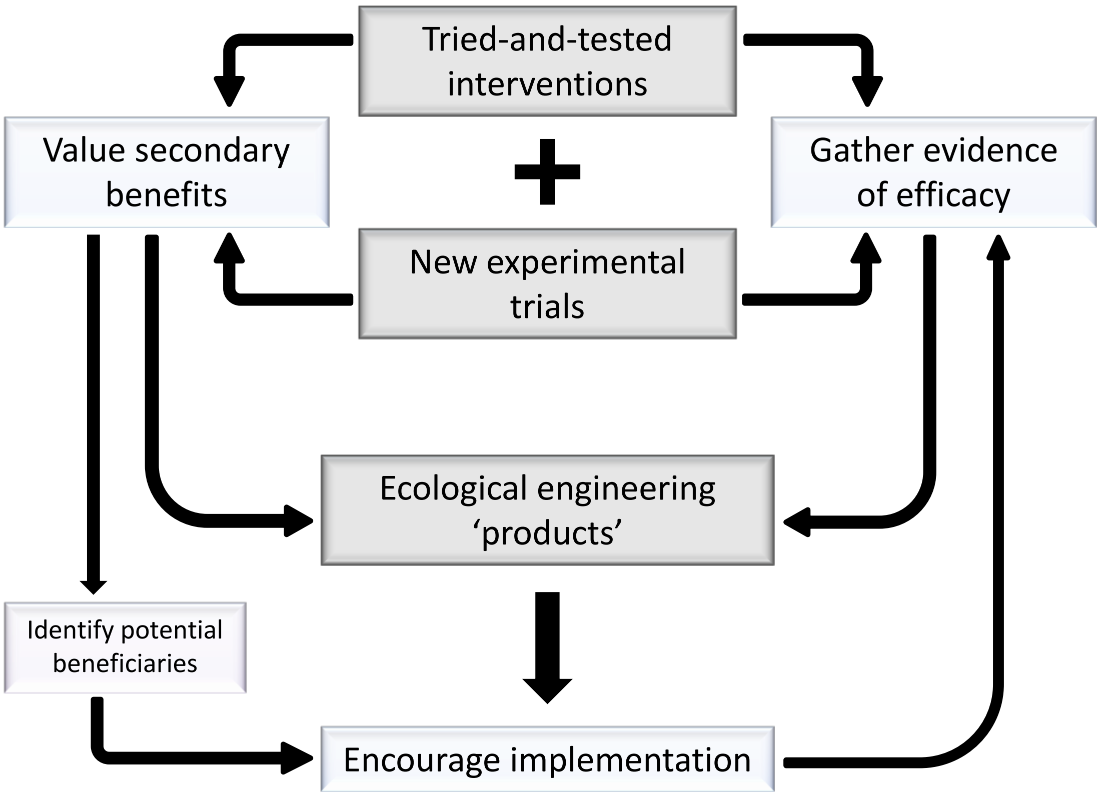

Figure 5.2 Schematic diagram illustrating necessary steps to effective implementation of multi-functional coastal defence developments that maximise secondary ecological benefits through design or engineering intervention.

A wealth of 'proof-of-concept' evidence exists globally to support methods of enhancing artificial marine structures for environmental, social and economic benefit (e.g. see reviews by Baine 2001, Moschella et al. 2005, Chapman and Underwood 2011, Firth et al. 2014b). There appears, however, to be limited awareness of this research amongst practitioners, since a lack of evidence regarding the efficacy of potential ecological enhancements was perceived (by stakeholders taking part in the perception study described in Chapter 4) to be one of the key barriers to implementation of multi-functional coastal defence developments. Holmes and Clark (2008) highlighted the importance of providing scientific information in a "*useful form*" (i.e. not necessarily in journal article format) to make it visible to, and usable by, policy-makers, regulators and practitioners (see also McNie 2007, Weichselgartner and Kasperson 2010). In the context of my research, I suggest that ecological engineering knowledge may be *usefully* communicated via an evolving catalogue of off-the-shelf enhancement 'products' that may be evaluated for implementation on the basis of: their predicted effects on biodiversity, their cost, their scope of application, and an indication of confidence that intended benefits would be realised. Lessons may be learned from the enterprise and resource development in terrestrial and freshwater systems. Tried-and-tested enhancements, such as bird and mammal boxes, have progressed from the research and development stage to become commercialised products that can be purchased and built-in to developments (e.g. structural housing blocks with internal cavities for swift nesting). Developers or consultants may browse online catalogues (e.g. http://www.habibat.co.uk/) for integrated habitat units that can satisfy a number of planning mitigation or enhancement requirements and provide space for nature in engineered developments. Valuation of intended secondary benefits would also be appropriate for a catalogue of interventions, yet a considerable amount of further research is necessary to reliably assess the non-use value of potential ecological secondary benefits (e.g. provision of habitat for conservation species) (Nunes and Van den Bergh 2001, Bräuer 2003, Costanza et al. 2014).

Another potential element of 'products' which requires considerable thought and debate is the key question of: *how much enhancement is enough*? To date, interventions in marine and coastal structures have been trialled primarily for experimentation purposes. Once at the implementation stage, it will be critical to understand density-dependent effects (e.g. Martins et al. 2010) of interventions when built-in to different types of structures, in order to ensure enhancements are proportionate to the scale of developments. There may be several alternative ways of defining what constitutes adequate and appropriate enhancement in different scenarios. For example, when installing artificial rock pools (or other habitat units) it may be a reasonable aim to mimic the density of rock pool habitat on nearby natural rocky shores. If the objective was to promote target species, however, then it may be more appropriate to consider scale in terms of population size and reproductive viability. Population viability analysis (PVA) and minimum viable population analysis (MVP) (Boyce 1992) have primarily been applied for conservation management of large vertebrates and endangered species (e.g. Murphy et al. 1990, Reed et al. 2003, Traill et al. 2007). There have also been attempts to assess the viability of metapopulations of invertebrates in discrete habitat patches (e.g. Tscharntke 1992, Ranius 2000). Little attention has been given, however, to assessing minimum viable population sizes for marine organisms (see Traill et al. 2007 for meta-analysis). There remain considerable uncertainties regarding the reliability of this approach to conservation management (Flather et al. 2011), particularly in the marine environment where replenishment of intertidal communities is complex and not well-understood (Schiel 2004). Nevertheless, there is certainly scope for further investigation.

In addition to translating existing tried-and-tested enhancement designs into ‘products’, there remains a need for development of additional novel designs, and also for additional testing of existing ones, in order to provide a broad tool kit of ecological engineering solutions necessary to deliver a range of secondary benefits appropriate for different scenarios. For example, two rock pool interventions trialled in Sydney Harbour were effective for enhancing biodiversity on vertical walls in a sheltered harbour (Chapman and Blockley 2009, Browne and Chapman 2014), but would be unlikely to be appropriate on an exposed open shore where coastal defences are often required. The drill-cored rock pools I trialled in Chapter 3 provide a new design that is robust to high levels of disturbance in exposed environments, but are only replicable in horizontal or sloping surfaces. Further experimentation with drill-cored rock pools may lead to increases in the biodiversity enhancement that may be achieved (e.g. if larger pools support even more species-rich or more ‘natural’ communities), or alternatively to potential cost savings that may encourage wider implementation (e.g. if smaller pools, that are cheaper to install, could provide equivalent enhancement). In addition to refining the physical design of enhancements, it is also necessary to test existing designs more extensively, over longer timeframes and in a variety of biogeographic locations, to understand their performance under different conditions and their scope of application. My conclusions regarding the efficacy of drill-cored rock pools after 24 months of monitoring would have been different to my conclusions presented in this thesis after 30 months (which I do not yet consider to be final outcomes, since climax communities have not been reached). For example, after 24 months, the communities in deeper drill-cored pools were not significantly different to those in shallower pools, whereas after 30 months they supported clearly different species in different relative abundances. Although the importance of long-term monitoring is widely-acknowledged (Hawkins et al. 2013a, 2013b), few published studies have monitored ecological engineering outcomes over timescales beyond 24 months (e.g. <10 months: Martins et al. 2010, Browne and Chapman 2014; 10-20 months: Chapman and Blockley 2009, Firth et al. 2014b, Perkol-Finkel and Sella 2015; but see Chapman and Underwood 2011: >24 months). Early publication may be advantageous for providing *some* evidence of the potential of enhancements as early as possible (e.g. ongoing studies described in Firth et al. 2014b, Browne and Chapman 2014, Evans et al. 2015), providing limitations are clearly highlighted and monitoring continues over longer periods subsequently.

The predictive model that I describe in Chapter 2 may also be considered an ecological engineering ‘product’, although not an enhancement intervention itself. In addition to the suggested improvements and further testing outlined in Chapter 2 (e.g. including additional predictor variables, testing in different biogeographic regions, etc.), it may be possible to apply this statistical approach to the outcomes of engineering enhancements themselves. Given a growing catalogue of enhancement ‘products’ that have been tried-and-tested in different structures and locations, a ‘Product type’ predictor variable may reasonably be added to the model to forecast smaller-scale ecological responses to engineering design options (i.e. rather than whole-structure scale responses).

Finally, in light of the apparent lack of visibility and awareness of existing evidence for different ecological engineering interventions, it may be necessary for researchers to take a pro-active role in communicating, and encouraging implementation of, current and future 'products' to practitioners and policy-makers. It is unrealistic to expect practitioners across different sectors to keep abreast of the rapidly-expanding body of academic literature in this field (Holmes and Clark 2008). The role of 'knowledge brokers' (Naylor et al. 2012; also referred to as 'interpreters': Holmes and Clark 2008, and 'boundary organisations': McNie 2007) is, therefore, extremely important in connecting researchers with industry, environmental managers and policy-makers. In the UK, the independent non-profit body CIRIA (the Construction Industry Research and Information Association, www.ciria.org) has emerged as an effective intermediary group in the field of ecological engineering and green infrastructure. CIRIA recognised our artificial rock pool enhancement (Chapter 3) as an innovative and effective design which would be of value to the construction industry. They particularly endorsed the simplicity and affordability of the enhancement, and the experimental rigor and monitoring with which its long-term efficacy was evaluated. Consequently, this research has been included as a case study in CIRIA's recent Coastal and Marine Environmental Site Guide publication (CIRIA 2015), which outlines best practice guidelines for marine and coastal construction work. The impact from this, coupled with promotion of the research at industry-focused workshop events (e.g. URBANE Project Final Stakeholder Workshop, 2013; CIRIA CPD Course/Workshop 'Working with nature to enhance hard infrastructure assets'; see web links in Chapter 4), has generated interest from developers and statutory bodies, and may result in implementation within several proposed coastal developments in the UK in the coming years.

If emerging evidence can continue to be effectively communicated to policy-makers and practitioners, then partnership funding may be attracted from identified beneficiaries of secondary benefits, and more specific policies may develop to strengthen the legislative framework in which secondary benefits are considered. This would provide the incentive and confidence required to encourage engagement and communication between sectors about multi-functional options during the planning stage of new developments. It is critical, however, that the current perceived lack of evidence does not become an obstacle to implementation, since implementation, with rigorous experimental control and long-term monitoring, is necessary in order to gather further evidence (Bulleri and Chapman 2010, Chapman and Underwood 2011, Naylor et al. 2012; see also Chapter 4).

5.3 Conclusion

As policy and legislation begins to recognise the need for developers to take a more pro-active role in protecting and enhancing the natural environment (e.g. HM Government 2011), my research provides some much-needed clarity on what can be done to deliver secondary ecological and socio-economic benefits from coastal defence developments. The outcomes include two potentially-valuable management tools to aid planning and decision-making for coastal defence developments: a predictive model to forecast the communities that can be expected to colonise different structures in different locations; and a proven means of enhancing the biodiversity on structures, through engineering intervention (i.e. drill-cored rock pools). Given the rapid proliferation of artificial structures in marine and coastal environments globally, and their associated impacts on the natural environment, it is critical that ecologically-sensitive engineering designs are widely incorporated into both new and existing developments. It is also important, however, to recognise that ecological secondary benefits that can be built-in to engineered structures do not constitute mitigation or compensation for the loss of natural habitats and species. The provision of ecological secondary benefits from multi-functional structures, therefore, should not be prioritised over more sustainable options for flood and coastal erosion risk management. Where 'hard' structures are considered appropriate and necessary for coastal development, however, opportunities must be taken to maximise ecological benefits as well as to minimise environmental impacts.

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APPENDIX I

MNCR SACFOR abundance scales

MNCR site and littoral habitat descriptors

MNCR SACFOR abundance scales

S = Superabundant, A = Abundant, C = Common, F = Frequent, O = Occasional, R = Rare

GROWTH FORM			**SIZE OF INDIVIDUALS / COLONIES**					
% COVER	**CRUST / MEADOW**	**MASSIVE / TURF**	**<1 cm**	**1-3 cm**	**3-15 cm**	**>15 cm**	**DENSITY**	
>80%	S		S				>1 / 0.0001 m^2 (1x1 cm)	>10,000/ m^2
40-79%	A	S	A	S			1-9 / 0.001 m^2 (3.16x3.16 cm)	1000-9999 / m^2
20-39%	C	A	C	A	S		1-9 / 0.01 m^2 (10x10 cm)	100-999 / m^2
10-19%	F	C	F	C	A	S	1-9 / 0.1 m^2	10-99 / m^2
5-9%	O	F	O	F	C	A	1-9 / m^2	
1-5% or density	R	O	R	O	F	C	1-9 / 10 m^2 (3.16x3.16 m)	
<1% or density		R		R	O	F	1-9 / 100 m^2 (10x10 m)	
					R	O	1-9 / 1000 m^2 (31.6x31.6 m)	
						R	>1 / 10,000 m^2 (100x100 m)	<1 / 1000 m^2

PORIFERA	Crusts *Halichondria*	Massive spp. *Pachymatisma*		Small solitary *Grantia*	Large solitary *Stelligera*	
HYDROZOA		Turf species *Tubularia* *Abietinaria*		Small clumps *Sarsia* *Aglaophenia*	Solitary *Corymorpha* *Nemertesia*	
ANTHOZOA	*Corynactis*	*Alcyonium*		Small solitary *Epizoanthus* *Caryophyllia*	Med. Solitary *Virgularia* *Cerianthus* *Urticina*	Large solitary *Eunicella* *Funiculina* *Pachycerianthus*
ANNELIDA	*Sabellaria spinulosa*	*Sabellaria alveolata*	*Spirorbis*	Scale worms *Nephtys* *Pomatoceros*	*Chaetopterus* *Arenicola* *Sabella*	
CRUSTACEA	Barnacles Tubiculous amphipods		*Semibalanus* Amphipods	*B. balanus* *Anapagurus* *Pisidia*	*Pagurus* *Galathea* Small crabs	*Homarus* *Nephrops* *Hyas araneus*
MOLLUSCA	*Mytilus* *Modiolus*		Small gastropod *L. neritoides* Small bivalves *Nucula*	Chitons Med. gastropod *L. littorea* *Patella* Med. bivalves *Mytilus* *Pododesmus*	Large gastropod *Buccinum* Lge bivalves *Mya, Pecten* *Arctica*	
BRACHIOPODA				*Neocrania*		
BRYOZOA	Crusts	*Pentapora* *Bugula Flustra*			*Alcyonidium* *Porella*	
ECHINO-DERMATA				*Echinocyamus* *Ocnus*	*Antedon* Small starfish Brittlestars *Echinocardium* *Aslia, Thyone*	Large starfish *Echinus* *Holothuria*
ASCIDIACEA	Colonial *Dendrodoa*			Small solitary *Dendrodoa*	Large solitary *Ascidia, Ciona*	*Diazona*
PISCES					Gobies Blennies	Dog fish Wrasse
PLANTS	Crusts, Maerl *Audouinella* Fucoids, Kelp *Desmarestia*	Foliose Filamentous			*Zostera*	Kelp *Halidrys* *Chorda* *Himanthalia*

Examples of groups or species for each category

(Hiscock 1996)

Survey no. | |
Site no. | |

Field site no. | |
No. of habitat records | |

MARINE NATURE CONSERVATION REVIEW

SITE

JOINT NATURE CONSERVATION COMMITTEE

LOCATION

Site name ______
Survey area ______
District (Scotland only) ______
County / Region ______

POSITION (Grid Reference or Latitude / Longitude)

Centre of site (required) ______
For extensive sites (optional) From ______ To ______

Position derived from: [ ] OS map [ ] Admiralty chart [ ] Decca [ ] GPS [ ] Differential GPS
Datum used: [ ] WGS72 [ ] WGS84 [ ] Other (state):

SURVEY DETAILS

	Visit 1	Visit 2
Surveyors	1	1
	2	2
	3	3
	4	4
Date (dd:mm:yy)	: :	: :
Time at start (h:m)	:	:
Duration of survey (h:m)	:	:
Underwater visibility (m)		
Height / depth of survey(m)		
Tidal correction (m)		
Measured from sea level:	Upper / Lower	Upper / Lower
Corrected to Chart Datum:	Upper / Lower	Upper / Lower

TYPE OF SURVEY

Zone
[ ] Littoral
[ ] Sublittoral

Recording
[ ] Inventory/map (biotope types only)
[ ] Intermediate *in situ* (habitat / main spp.)
[ ] Intermediate remote (habitat / main spp.)
[ ] Detailed (habitat / all spp.)
[ ] Other (state):

Sampling
[ ] Cores (shore: 11 cm diam.)
[ ] Cores (diver: 10.3 cm diam.)
[ ] Dredge - anchor
[ ] Dredge - biological
[ ] Grab - Day
[ ] Grab - Van Veen
[ ] Granulometry sample
[ ] Suction sampler
[ ] Trawl - Agassiz
[ ] Other (state):

Sieve size
[ ] 0.5 mm mesh
[ ] 1.0 mm mesh
[ ] Other (state):

Images
[ ] Photography
[ ] Video

Sonar
[ ] RoxAnn
[ ] Sidescan

PHOTOGRAPHY

	Photographer	No. taken	Equipment used (camera & lens)
Aerial			
Views / landscapes			
Habitats			
Species (close-up)			

PHYSIOGRAPHIC TYPE

- Open coast
  - – Linear coast
  - – Islands / rocks
  - – Offshore seabed
  - – Semi-enclosed coast
  - – Strait / Sound
  - – Barrier beach
- Enclosed coast
  - – Embayment
  - – Sealoch
  - – Ria /Voe
  - – Estuary
  - – Isolated saline water (lagoon)

* SALINITY

Full	(30-40‰)
Variable	(18-40‰)
Reduced	(18-30‰)
Low	(<18‰)
Not known	
‰ Measured	

* WAVE EXPOSURE

- **Extremely exposed** (prevailing wind / swell onshore, deep water)
- **Very exposed** (prevailing wind and swell onshore)
- **Exposed** (prevailing wind onshore, offshore shallows / obstructions)
- **Moderately exposed** (prevailing wind offshore but onshore wind frequent)
- **Sheltered** (restricted [<20 km] fetch; offshore shallows / obstructions)
- **Very sheltered** (fetch <20 km in any direction and <3 km to prevailing wind)
- **Extremely sheltered** (fully enclosed, fetch <3 km)
- **Ultra sheltered** (fetch of few 10s or at most 100s m)

* TIDAL STREAMS

(maximum at surface)

Very strong	(>6 kn.)
Strong	(3-6 kn.)
Moderately strong	(1-3 kn.)
Weak	(<1 kn.)
Very weak	(negligible)
Not known	

GEOLOGY

- Hard
  - – Igneous
  - – Chert / Flint
  - – Slate
  - – Sand / Mudstone
- Moderately hard
  - – Limestone
- Friable
  - – Slate / Shale
- Soft
  - – Sand / Mudstone
  - – Chalk
- Very soft
  - – Clay
  - – Peat
- Not known

STRATIFICATION

(sublittoral sites only)

- Thermocline
- Halocline
- Not stratified

°C Temperature – surface

°C – bottom

LITTORAL WIDTH

HWST-LWST (littoral sites only)

- <1 m
- 1-10 m
- 10-100 m
- 100-1000 m
- >1000 m

LITTORAL ASPECT

(littoral sites only)

- North
- North-east
- East
- South-east
- South
- South-west
- West
- North-west

CONSERVATION ASSESSMENT

- Unspoilt / natural
- Representative (for sector)
- Rare / unusual biotopes
- Rare species
- High species richness
- High biotope richness
- Fragile species present
- Fragile biotopes present
- Intrinsic appeal
- Ornithological interest
- Seal haul out

SITE DESIGNATIONS

(state 'p' for proposed)

- Area of Outstanding Nat. Beauty
- Biosphere Reserve
- County Wildlife Trust Reserve
- Heritage Coast
- Local Nature Reserve
- Marine Consultation Area (Scotland)
- Marine Nature Reserve
- Ministry of Defence
- National Nature Reserve
- National Park
- National Scenic Area
- National Trust / NT for Scotland
- RAMSAR Site
- RSPB Reserve
- Sensitive Marine Area (England)
- Site of Special Scientific Interest
- Special Area of Conservation
- Special Protection Area
- Voluntary Marine Nature Reserve
- World Heritage Site
- ....

USES AND IMPACTS

- Fishing – netting
  - – trawling
  - – angling
  - – potting
- Collection – bait digging
  - – shellfish
  - – algae
- Boulder turning for peelers
- Extraction – sand / gravel
  - – maerl
  - – oil / gas
- Aqua culture – fin-fish
  - – shellfish
  - – algae
- Coastal defence – sea walls
  - – dredging
  - – groynes
- Land claim
- Military use
- Sewage discharge
- Waste dumping
- Industrial waste discharge
- Litter and debris
- Oil / tar / chemicals
- Educational / scientific study
- Recreational – facilities
  - – resort
  - – marina
  - – popular beach
  - – water sports
  - – dive site
  - – wind surfing
- Mooring / beaching / launching
- Evidence of physical damage
- ....

* Apply to site as a whole; local variations can be noted on individual habitat forms

Survey no.

Site no.

Field site no.

MARINE NATURE CONSERVATION REVIEW

LITTORAL HABITAT (DETAILED)

JOINT NATURE CONSERVATION COMMITTEE

Site name:

Hab. no.	Position within site (extensive sites only)	No. of cores	Sieved vol. (l)	Infaunal sample no.	Granul. sample no.

SURVEYORS

m HEIGHT LIMITS
- Upper (from sea level)
- Lower "
- Upper (from chart datum)
- Lower "

✓ HEIGHT BAND
- Strandline
- Upper shore
- Mid shore
- Lower shore

✓ ZONE
- Supralittoral
- Littoral fringe
  - upper
  - lower
- Eulittoral
  - upper
  - mid
  - lower
- Sublittoral fringe
- Not applicable

✓ EXTENT OF RECORD
- Multiple habitats (whole area)
- Zone / height band
- Restricted feature

✓ SURVEY QUALITY
Flora Fauna
- Thorough
- Adequate
- Incomplete

% SUBSTRATUM
- Bedrock
- Boulders
  - very large >1024 mm
  - large 512-1024 mm
  - small 256-512 mm
- Cobbles 64-256 mm
- Pebbles 16-64 mm
- Gravel 4-16 mm
  - stone
  - shell
  - dead maerl
  - live maerl
- Sand
  - coarse 1-4 mm
  - medium 0.25-1 mm
  - fine 0.063-0.25 mm
- Mud <0.063 mm
- Shells (empty)
- Artificial
  - metal
  - concrete
  - wood
- Trees / branches
- Algae
- ....

100 Total

% INCLINATION
- Overhangs
- Vertical faces (80-100°)
- Very steep faces (40-80°)
- Upper faces (0-40°)
- Underboulders

100 Total

1-5 FEATURES - ROCK
- Surface relief (even-rugged)
- Texture(smooth-pitted)
- Stability (stable-mobile)
- Scour (none-scoured)
- Silt (none-silted)
- Fissures >10mm (none-many)
- Crevices <10mm (none-many)
- Rockpools (none-all)
- Boulder/cobble/pebble shape (rounded-angular)

✓
- Gully
- Cave
- Rockmill
- Boulder/cobble - on rock
- Boulder/cobble - on sediment
- Boulder holes
- Sediment on rock

✓ MODIFIERS
- Freshwater runoff
- Wave exposure - wave surged
  - sheltered
- Tidal streams - accelerated
  - decelerated
- Grazing
- Shading
- Pollution

1-5 FEATURES - SEDIMENT
- Surface relief (even-uneven)
- Firmness (firm-soft)
- Stability (stable-mobile)
- Sorting (well-poor)
- Black layer (1=not visible, 2=>20 cm, 3=5-20 cm, 4=1-5 cm, 5=<1 cm)

✓
- Mounds / casts
- Burrows / holes
- Tubes
- Algal mat
- Waves / dunes (>10 cm high)
- Ripples(<10 cm high)
- Drainage channels / creeks
- Standing water
- Subsurface coarse layer
- Subsurface clay / mud
- Surface silt / flocculent

1-5 ASSESSMENT
- Representativeness (atyp/tran/typ)
- Naturalness (unnat.-nat.)
- Extent (limit.-exten.)
- Species richness (low-high)
- Abundance/biomass(low-high)

MAIN COVER OR CHARACTERISING SPECIES / TAXA

Abund.	Species / taxon

Appendix II

Cluster analyses underlying categorical predictor variables

Cluster analyses underlying categorical predictor variables

Surrounding habitat

The composition of the surrounding habitat was recorded within approximately 1 km of each structure. The percentage of each type of littoral substratum (i.e. bedrock, boulders, cobbles, pebbles, gravel, sand, mud, empty shells, artificial) was visually estimated, according to the 'Substratum' categories outlined in the MNCR littoral habitat descriptors (Hiscock 1996; Appendix I). Hierarchical cluster analysis was used to identify natural groupings of sites according to multivariate substratum compositions. Clusters were identified using the group-average linkage method in PRIMER v6 (PRIMER-E Ltd. Version 6, 2006), based on Bray-Curtis similarities between sites.

From inspection of the resulting dendrogram (Figure 1), in conjunction with the raw percentage composition data, four broad categories of 'Surrounding habitat' were identified and described (~ 58-85% similarity; Table 1).

Table 1 Broad categories of 'Surrounding habitat' recorded around (within approx. 1 km) 125 intertidal coastal defence structures surveyed around the coast of Wales, UK.

Cluster group: Visually defined from dendrogram of hierarchical cluster analysis with average group linkage (Figure 1)

Cluster group	'Surrounding habitat' category	Description
R	Rocky	Predominantly bedrock habitat with some boulders, cobbles and soft sediments.
MX	Mixed	Mosaic of bedrock, boulders, cobbles and soft sediments.
S	Sandy	Predominantly sand, but with some bedrock, boulders, cobbles and other soft sediments.
M	Muddy	Predominantly mud and sand, with some gravel and pebbles.

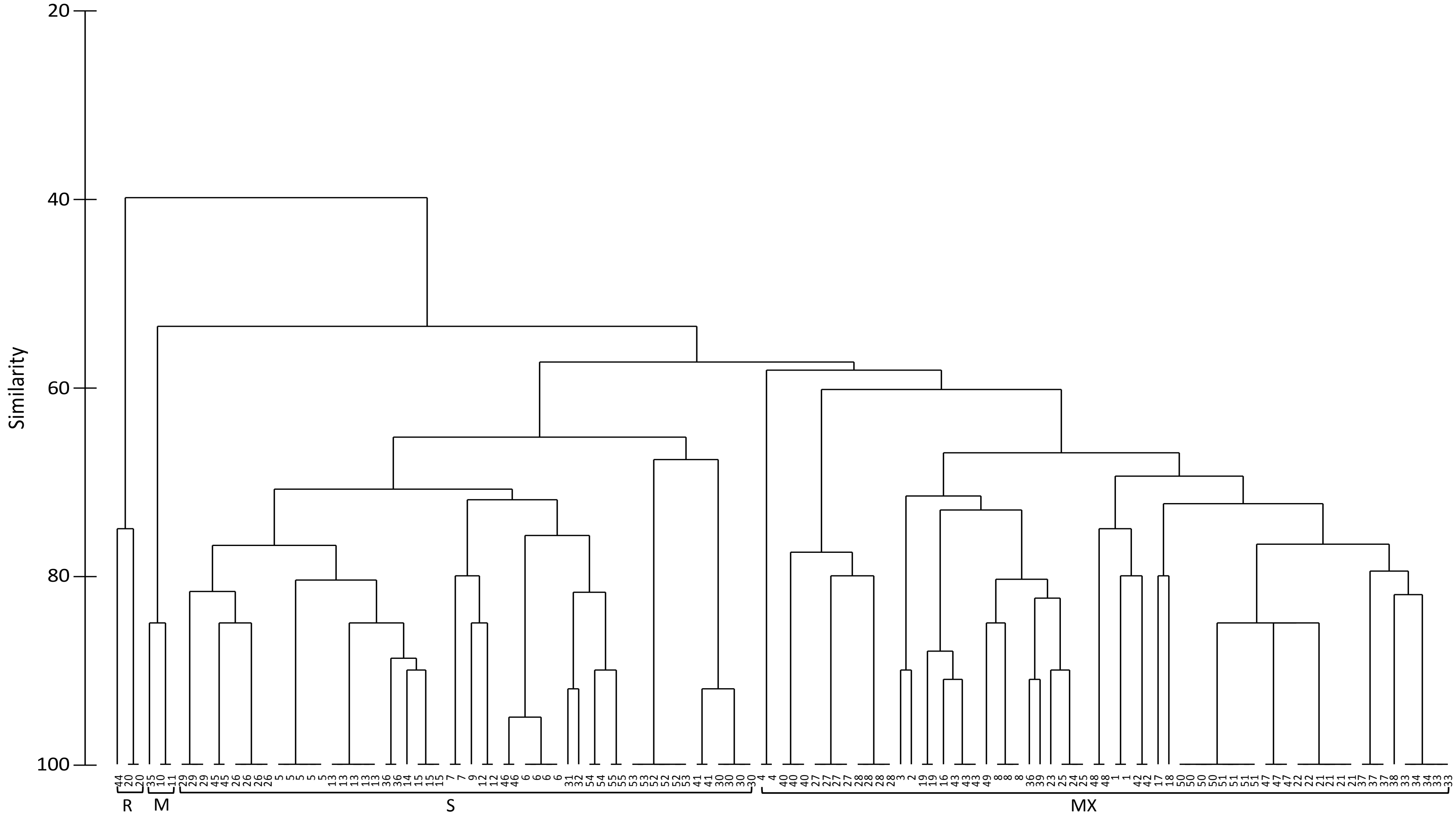

Figure 1 Intertidal coastal defence structures (n = 125, labelled by location #) clustered by group average linkage of Bray-Curtis resemblances between multivariate percentages of littoral substratum types contributing to the surrounding habitat (within approx. 1 km of structures). Four clusters of ‘Surrounding habitat’ (R, M, S, MX) are described in Table 1.

Surface inclination

The percentage of different surface inclinations on each structure (i.e. overhangs, vertical, very steep, upper, underboulders) was visually estimated, according to the 'Inclination' categories outlined in the MNCR littoral habitat descriptors (Hiscock 1996; Appendix I). Hierarchical cluster analysis was used to identify natural groupings of structures according to multivariate surface inclinations. Clusters were identified using the group-average linkage method in PRIMER v6 (PRIMER-E Ltd. Version 6, 2006), based on Bray-Curtis similarities between sites.

From inspection of the resulting dendrogram (Figure 2), in conjunction with the raw percentage inclination data, three broad categories of 'Surface inclination' were identified and described (56-70% similarity; Table 2). Two outliers with 100% 'very steep' inclination were assigned to the 'Vertical-Very steep' inclination category, accordingly (Cluster V).

Table 2 Broad categories of 'Surface inclination' on 125 intertidal coastal defence structures surveyed around the coast of Wales, UK.

Cluster group: Visually defined from dendrogram of hierarchical cluster analysis with average group linkage (Figure 2)

Cluster group	'Surface inclination' category	Description
V	Vertical-Very steep	Predominantly vertical or very steep surfaces (>70%), occasionally with some upper and overhangs.
MX	Mixed	Mixture of vertical surfaces, very steep, upper, overhangs and underboulders.
U	Upper (>50%)	Predominantly upper surfaces (>50%), with some vertical and very steep, occasionally with overhangs and underboulders.

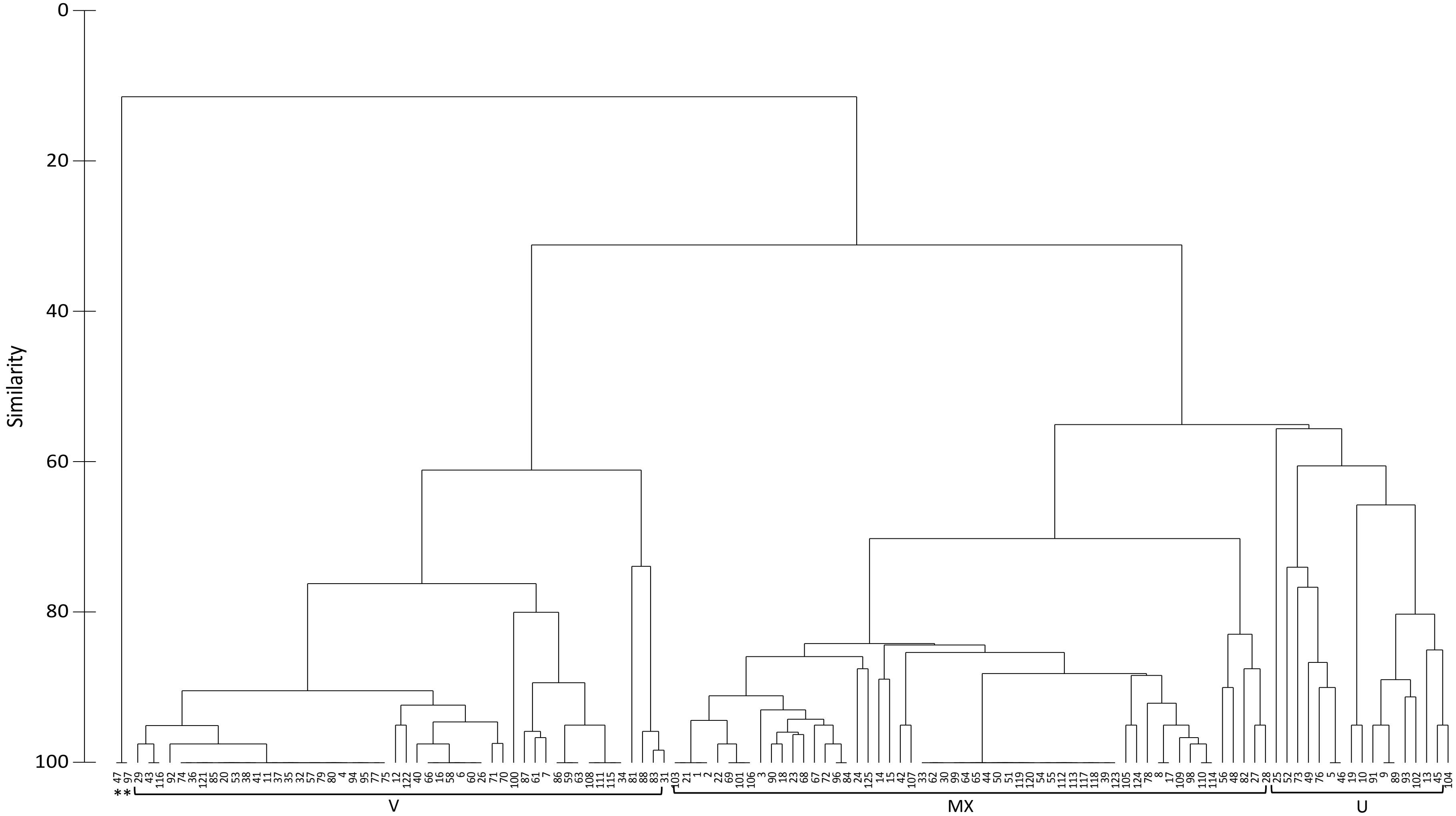

Figure 2 Intertidal coastal defence structures (n = 125) clustered by group average linkage of Bray-Curtis resemblances between multivariate percentages of substratum inclination. Four clusters of ‘Surface inclination’ (V, MX, U) are described in Table 2; **two outliers were identified (see text for explanation).

Appendix III

List of colonising taxa

Characteristic community SIMPER analyses

Table 1 Species and morphotaxa recorded on 125 intertidal coastal defence structures surveyed around Wales, UK.

Species and morphotaxa

Red macroalgae
Catenella caespitosa
Ceramium sp.
Chondracanthus acicularis
Chondrus crispus
Corallina officinalis
Cystoclonium purpureum
Gastroclonium ovatum
Gracilaria gracilis
Heterosiphonia plumosa
Laurencia obtusa
Lithothamnia
Lomentaria articulata
Mastocarpus stellatus
Membranoptera alata
Osmundea osmundea
Osmundea sp.
Palmaria palmata
Phycodrys rubens
Plocamium cartilagineum
Polysiphonia elongata
Polysiphonia lanosa
Polysiphonia sp.
Porphyra sp.
Pterosiphonia parasitica
Red crinkly
Red encrusting
Red turf
Rhodomela confervoides
Rhodothamniella floridula
Spyridia filamentosa

Green macroalgae
Cladophora rupestrus
Cladophora sp.
Codium fragile
Rhizoclonium riparium
Ulva sp.

Mobile crustaceans
Amphipod sp.
Cancer pagurus
Carcinus maenas
Idotea granulosa
Ligia oceanica
Necora puber
Paguridae sp.
Palaemon sp.
Portunidae sp.

Brown macroalgae
Ascophyllum nodosum
Brown branched
Brown encrusting
Brown filamentous
Brown jelly
Chorda filum
Cladostephus spongiosus
Fucus ceranoides
Fucus sp. juv.
Fucus serratus
Fucus spiralis
Fucus vesiculosus
Laminaria digitata
Leathesia difformis
Pelvetia canaliculata
Petalonia fascia
Saccharina latissima
Scytosiphon lomentaria

Bryozoans
Alcyonidium sp.
Bowerbankia sp.
Bryozoa crust orange
Bryozoa crust white
Bugula plumosa
Buguloidea sp.
Dynamena pumila

Hydroids
Hydrallmania falcata
Hydroid sp.

Sponges
Porifera crust orange
Porifera crust yellow

Polychaetes
Eulalia viridis
Lanice conchilega
Sabellaria alveolata
Spirobranchus sp.
Spirorbis sp.
Terebellidae sp.

Barnacles
Austrominius modestus
Balanus perforatus
Chthamalus sp.
Semibalanus balanoides

Ascidians
Molgula sp.

Anemones
Actinia equina
Actinia fragacea
Anemone sp.
Anemonia viridis
Aulactinia verrucosa
Metridium senile
Sagartia elegans
Sagartia troglodytes

Molluscs
Cerastoderma edule
Crepidula fornicata
Gibbula cineraria
Gibbula umbilicalis
Littorina littorea
Littorina obtusata
Littorina saxatilis
Melarhaphe neretoides
Mytilus edulis
Mytilus edulis juv.
Nucella lapillus
Ocenebra erinacea
Onchidoris bilamellata
Patella depressa
Patella vulgata
Phorcus lineatus
Polyplacophora sp.

Insects
Anurida maritima
Chironomidae sp. juv.

Echinoderms
Asterias rubens

Fish
Fish sp.

Table 2 Taxa contributing to similarities among communities within characteristic community Group A (SIMPER analyses: Clarke 1993).

Av. abundance: numerical scale reflecting average SACFORN abundances (6 = S, 5 = A, 4 = C, 3 = F, 2 = O, 1 = R, 0 = N); %: percent contribution to multivariate similarity; Cum. %: cumulative percent contribution to multivariate similarity; Sim/SD: similarity divided by standard deviation of contributions across all pairs of samples (measure of consistency of contribution)

Average similarity = 51.1					
Species	**Av. abundance**	**Av. similarity**	**Sim/ SD**	**%**	**Cum. %**
Ulva sp.	4.67	15.25	15.28	29.88	29.88
Fucus sp. juv.	4.00	11.71	9.61	22.94	52.82
Littorina saxatilis	3.00	10.62	15.49	20.80	73.62
Fucus spiralis	2.67	3.70	0.58	7.26	80.87
Pelvetia canaliculata	2.33	3.70	0.58	7.26	88.13
Porphyra sp.	2.67	3.64	0.58	4.12	95.25
Chthamalus sp.	1.67	2.42	0.58	4.75	100.00
Idotea granulosa	1.67	0.00	-	0.00	100.00
Mastocarpus stellatus	1.67	0.00	-	0.00	100.00
Amphipod sp.	1.00	0.00	-	0.00	100.00
Catenella caespitosa	1.00	0.00	-	0.00	100.00
Patella vulgata	1.00	0.00	-	0.00	100.00
Semibalanus balanoides	1.00	0.00	-	0.00	100.00

Table 3 Taxa contributing to similarities among communities within characteristic community Group B (SIMPER analyses: Clarke 1993).

Av. abundance: numerical scale reflecting average SACFORN abundances (S = 6, A = 5, C = 4, F = 3, O = 2, R = 1, 0 = Not recorded); %: percent contribution to multivariate similarity; Cum. %: cumulative percent contribution to multivariate similarity; Sim/SD: similarity divided by standard deviation of contributions across all pairs of samples (measure of consistency of contribution)

Average similarity = 55.6					
Species	**Av. abundance**	**Av. similarity**	**Sim/ SD**	**%**	**Cum. %**
Fucus spiralis	4.87	5.34	3.38	9.61	9.61
Ascophyllum nodosum	4.43	4.40	1.49	7.91	17.52
Catenella caespitosa	3.74	3.83	1.76	6.88	24.41
Ulva sp.	3.52	3.80	3.64	6.84	31.25
Fucus sp. juv.	3.48	3.72	4.10	6.70	37.95
Pelvetia canaliculata	3.61	3.46	1.50	6.22	44.17
Semibalanus balanoides	3.26	2.81	1.89	5.05	49.22
Amphipod sp.	3.30	2.73	1.28	4.92	54.14
Austrominius modestus	3.43	2.69	1.49	4.84	58.98
Fucus vesiculosus	2.83	2.04	1.10	3.67	62.65
Littorina littorea	2.78	1.97	1.22	3.54	66.19
Ceramium sp.	2.74	1.82	0.78	3.27	69.46
Patella vulgata	2.52	1.71	1.01	3.08	72.53
Littorina obtusata	2.30	1.70	1.18	3.06	75.59
Polysiphonia sp.	2.17	1.34	0.71	2.41	78.00
Littorina saxatilis	2.04	1.28	0.81	2.29	80.29
Mytilus edulis	1.96	1.17	0.80	2.10	82.39
Lithothamnia	1.96	1.03	0.65	1.86	84.25
Chondrus crispus	1.65	0.90	0.70	1.63	85.87
Cladophora rupestrus	1.57	0.85	0.53	1.52	87.40
Actinia equina	1.61	0.84	0.69	1.51	88.90
Portunidae sp.	1.43	0.70	0.60	1.25	90.16
Fucus serratus	1.65	0.65	0.55	1.17	91.33
Chthamalus sp.	1.48	0.64	0.56	1.15	92.48
Anurida maritima	1.70	0.64	0.45	1.15	93.63
Nucella lapillus	1.43	0.57	0.54	1.02	94.65
Porphyra sp.	1.17	0.54	0.62	0.97	95.62
Dynamena pumila	1.17	0.48	0.38	0.86	96.48
Carcinus maenas	1.17	0.43	0.36	0.77	97.25
Melarhaphe neretoides	0.96	0.22	0.28	0.39	97.64
Mytilus edulis juv.	0.78	0.20	0.28	0.35	97.99
Hydroid sp.	0.78	0.17	0.25	0.31	98.30
Alcyonidium sp.	0.74	0.17	0.24	0.31	98.61
Red algal turf	0.74	0.12	0.23	0.22	98.82
Mastocarpus stellatus	0.61	0.11	0.20	0.19	99.02
Lomentaria articulata	0.65	0.08	0.18	0.15	99.16

Idotea granulosa	0.52	0.07	0.15	0.13	99.30
Gibbula umbilicalis	0.48	0.07	0.19	0.13	99.43
Ligia oceanica	0.52	0.06	0.13	0.10	99.53
Fucus ceranoides	0.57	0.05	0.11	0.10	99.63
Cladostephus spongiosus	0.43	0.05	0.15	0.08	99.71
Brown filamentous algae	0.39	0.03	0.11	0.05	99.76
Bryozoa crust white	0.35	0.03	0.11	0.05	99.81
Rhizoclonium riparium	0.30	0.02	0.11	0.04	99.85
Porifera crust orange	0.22	0.01	0.11	0.02	99.87
Spirobranchus sp.	0.26	0.01	0.06	0.02	99.89
Spirorbis sp.	0.30	0.01	0.06	0.02	99.91
Palaemon sp.	0.39	0.01	0.06	0.02	99.93
Palmaria palmata	0.13	0.01	0.11	0.02	99.95
Phorcus lineatus	0.22	0.01	0.06	0.02	99.97
Osmundea sp.	0.17	0.01	0.06	0.01	99.98
Fish sp.	0.26	0.01	0.06	0.01	99.99
Corallina officinalis	0.17	0.00	0.06	0.01	100.00
Rhodothamniealla floridula	0.22	0.00	-	0.00	100.00
Bryozoa crust orange	0.13	0.00	-	0.00	100.00
Cerastoderma edule	0.13	0.00	-	0.00	100.00
Chondracanthus acicularis	0.13	0.00	-	0.00	100.00
Osmundea osmundea	0.13	0.00	-	0.00	100.00
Polysiphonia lanosa	0.13	0.00	-	0.00	100.00
Brown encrusting algae	0.09	0.00	-	0.00	100.00
Cladophora sp.	0.09	0.00	-	0.00	100.00
Laurencia obtusa	0.09	0.00	-	0.00	100.00
Pterosiphonia parasitica	0.09	0.00	-	0.00	100.00
Red encrusting algae	0.09	0.00	-	0.00	100.00
Anemone sp.	0.04	0.00	-	0.00	100.00
Brown jelly algae	0.04	0.00	-	0.00	100.00
Chorda filum	0.04	0.00	-	0.00	100.00
Laminaria digitata	0.04	0.00	-	0.00	100.00
Leathesia difformis	0.04	0.00	-	0.00	100.00
Sabellaria alveolata	0.04	0.00	-	0.00	100.00

Table 4 Taxa contributing to similarities among communities within characteristic community Group C (SIMPER analyses: Clarke 1993).

Av. abundance: numerical scale reflecting average SACFORN abundances (S = 6, A = 5, C = 4, F = 3, O = 2, R = 1, 0 = Not recorded); %: percent contribution to multivariate similarity; Cum. %: cumulative percent contribution to multivariate similarity; Sim/SD: similarity divided by standard deviation of contributions across all pairs of samples (measure of consistency of contribution)

Average similarity = 56.0					
Species	**Av. abundance**	**Av. similarity**	**Sim/ SD**	**%**	**Cum. %**
Ulva sp.	3.98	7.24	2.70	12.92	12.92
Austrominius modestus	4.19	6.72	2.12	11.99	24.91
Fucus spiralis	3.84	6.20	1.89	11.07	35.98
Fucus sp. juv.	2.98	5.39	2.64	9.62	45.61
Semibalanus balanoides	3.31	5.21	1.98	9.31	54.91
Patella vulgata	2.45	3.49	1.40	6.24	61.15
Littorina saxatilis	2.47	3.17	1.10	5.66	66.81
Littorina littorea	2.41	2.87	1.07	5.12	71.93
Porphyra sp.	1.95	2.50	1.01	4.47	76.40
Amphipod sp.	2.28	2.49	0.81	4.44	80.84
Chthamalus sp.	1.97	1.64	0.64	2.93	83.77
Actinia equina	1.64	1.64	0.79	2.93	86.70
Melarhaphe neretoides	1.64	1.18	0.50	2.11	88.81
Pelvetia canaliculata	1.55	1.15	0.49	2.06	90.86
Fucus vesiculosus	1.28	0.90	0.47	1.61	92.48
Nucella lapillus	1.42	0.90	0.50	1.61	94.09
Mytilus edulis	1.47	0.87	0.48	1.55	95.64
Mytilus edulis juv.	1.14	0.60	0.43	1.07	96.71
Catenella caespitosa	1.03	0.56	0.34	0.99	97.70
Anurida maritima	0.89	0.28	0.25	0.50	98.20
Littorina obtusata	0.45	0.17	0.23	0.30	98.50
Polysiphonia sp.	0.59	0.16	0.22	0.29	98.79
Ceramium sp.	0.61	0.13	0.18	0.24	99.02
Portunidae sp.	0.53	0.12	0.17	0.22	99.24
Hydroid sp.	0.50	0.10	0.16	0.18	99.43
Ascophyllum nodosum	0.36	0.07	0.15	0.12	99.54
Gibbula umbilicalis	0.31	0.06	0.12	0.10	99.64
Sabellaria alveolata	0.38	0.06	0.11	0.10	99.75
Chondrus crispus	0.33	0.05	0.11	0.10	99.84
Phorcus lineatus	0.27	0.02	0.05	0.04	99.89
Ligia oceanica	0.19	0.01	0.05	0.03	99.91
Fucus serratus	0.16	0.01	0.05	0.02	99.93
Idotea granulosa	0.16	0.01	0.05	0.02	99.95
Palaemon sp.	0.16	0.01	0.04	0.01	99.96
Lithothamnia	0.16	0.01	0.04	0.01	99.98
Carcinus maenas	0.09	0.00	0.04	0.01	99.98

Laurencia obtusa	0.09	0.00	0.04	0.01	99.99
Osmundea sp.	0.06	0.00	0.02	0.00	99.99
Mastocarpus stellatus	0.08	0.00	0.02	0.00	99.99
Red algal turf	0.06	0.00	0.02	0.00	100.00
Heterosiphonia plumosa	0.06	0.00	0.02	0.00	100.00
Palmaria palmata	0.06	0.00	0.02	0.00	100.00
Cladostephus spongiosus	0.05	0.00	0.02	0.00	100.00
Fucus ceranoides	0.08	0.00	-	0.00	100.00
Brown filamentous algae	0.05	0.00	-	0.00	100.00
Dynamena pumila	0.05	0.00	-	0.00	100.00
Eulalia viridis	0.05	0.00	-	0.00	100.00
Sagartia troglodytes	0.05	0.00	-	0.00	100.00
Spirorbis sp.	0.05	0.00	-	0.00	100.00
Bryozoa crust orange	0.03	0.00	-	0.00	100.00
Cancer pagurus	0.02	0.00	-	0.00	100.00
Chondracanthus acicularis	0.02	0.00	-	0.00	100.00
Cladophora rupestrus	0.02	0.00	-	0.00	100.00
Corallina officinalis	0.02	0.00	-	0.00	100.00
Ocenebra erinacea	0.02	0.00	-	0.00	100.00
Porifera crust orange	0.02	0.00	-	0.00	100.00

Table 5 Taxa contributing to similarities among communities within characteristic community Group D (SIMPER analyses: Clarke 1993).

Av. abundance: numerical scale reflecting average SACFORN abundances (S = 6, A = 5, C = 4, F = 3, O = 2, R = 1, 0 = Not recorded); %: percent contribution to multivariate similarity; Cum. %: cumulative percent contribution to multivariate similarity; Sim/SD: similarity divided by standard deviation of contributions across all pairs of samples (measure of consistency of contribution)

Average similarity = 49.2					
Species	**Av. abundance**	**Av. similarity**	**Sim/ SD**	**%**	**Cum. %**
Semibalanus balanoides	4.74	4.79	3.59	9.75	9.75
Ulva sp.	4.26	4.35	2.67	8.84	18.59
Patella vulgata	4.00	3.97	4.25	8.07	26.66
Fucus sp. juv.	2.96	2.84	2.28	5.77	32.42
Littorina littorea	2.96	2.67	1.63	5.44	37.86
Chondrus crispus	2.81	2.33	1.31	4.74	42.60
Fucus serratus	2.81	2.08	1.27	4.24	46.84
Nucella lapillus	2.56	2.08	1.29	4.24	51.08
Fucus vesiculosus	2.70	1.95	1.05	3.96	55.04
Actinia equina	2.52	1.93	1.18	3.93	58.97
Porphyra sp.	2.41	1.76	1.07	3.59	62.56
Chthamalus sp.	2.93	1.70	0.94	3.46	66.02
Fucus spiralis	2.48	1.59	0.96	3.24	69.26
Littorina saxatilis	2.41	1.40	0.88	2.84	72.09

Austrominius modestus	2.19	1.31	0.87	2.67	74.76
Ceramium sp.	2.30	1.30	0.83	2.65	77.41
Mastocarpus stellatus	1.93	0.98	0.62	2.00	79.41
Lithothamnia	1.93	0.79	0.66	1.62	81.03
Littorina obtusata	1.63	0.67	0.59	1.37	82.40
Gibbula umbilicalis	1.52	0.58	0.48	1.19	83.58
Polysiphonia sp.	1.56	0.58	0.51	1.17	84.76
Melarhaphe neretoides	1.63	0.56	0.51	1.14	85.90
Portunidae sp.	1.37	0.53	0.48	1.08	86.98
Sabellaria alveolata	1.41	0.51	0.44	1.04	88.02
Palmaria palmata	1.52	0.49	0.52	0.99	89.02
Catenella caespitosa	1.30	0.49	0.52	0.99	90.00
Cladostephus spongiosus	1.15	0.46	0.44	0.93	90.94
Amphipod sp.	1.07	0.36	0.35	0.73	91.67
Bryozoa crust white	1.07	0.34	0.42	0.69	92.36
Lomentaria articulata	1.15	0.31	0.39	0.64	93.00
Mytilus edulis	0.96	0.31	0.42	0.64	93.64
Dynamena pumila	0.93	0.26	0.28	0.53	94.17
Corallina officinalis	1.15	0.26	0.36	0.52	94.69
Porifera crust orange	0.93	0.25	0.40	0.51	95.20
Mytilus edulis juv.	0.93	0.24	0.37	0.48	95.68
Spirobranchus sp.	0.89	0.22	0.33	0.45	96.13
Ascophyllum nodosum	0.93	0.21	0.36	0.43	96.57
Phorcus lineatus	0.96	0.21	0.30	0.42	96.99
Spirorbis sp.	0.89	0.16	0.24	0.33	97.32
Hydroid sp.	0.89	0.15	0.24	0.30	97.62
Porifera crust yellow	0.70	0.14	0.29	0.28	97.90
Cladophora rupestrus	0.59	0.10	0.24	0.20	98.10
Pelvetia canaliculata	0.52	0.10	0.28	0.20	98.30
Osmundea sp.	0.78	0.09	0.19	0.19	98.49
Idotea granulosa	0.52	0.07	0.16	0.15	98.63
Laminaria digitata	0.70	0.07	0.17	0.14	98.77
Osmundea osmundea	0.63	0.07	0.16	0.14	98.91
Membranoptera alata	0.56	0.06	0.20	0.12	99.03
Patella depressa	0.37	0.06	0.17	0.12	99.14
Fucus ceranoides	0.59	0.06	0.09	0.11	99.25
Bryozoa crust orange	0.56	0.05	0.16	0.10	99.36
Red algal turf	0.41	0.05	0.16	0.10	99.46
Alcyonidium sp.	0.48	0.04	0.16	0.08	99.54
Leathesia difformis	0.37	0.03	0.13	0.06	99.60
Laurencia obtusa	0.41	0.03	0.09	0.05	99.65
Bowerbankia sp.	0.37	0.02	0.09	0.05	99.70
Lanice conchilega	0.44	0.02	0.09	0.04	99.74
Rhizoclonium riparium	0.33	0.02	0.09	0.04	99.79
Carcinus maenas	0.30	0.02	0.09	0.04	99.83
Heterosiphonia plumosa	0.33	0.02	0.09	0.03	99.86

Chondracanthus acicularis	0.30	0.01	0.05	0.02	99.88
Brown filamentous algae	0.19	0.01	0.05	0.02	99.90
Fish sp.	0.15	0.01	0.05	0.02	99.92
Rhodomela confervoides	0.30	0.01	0.05	0.01	99.93
Saccharina latissima	0.22	0.01	0.05	0.01	99.94
Hydrallmania falcata	0.22	0.00	0.05	0.01	99.95
Brown jelly algae	0.15	0.00	0.05	0.01	99.96
Anurida maritima	0.22	0.00	0.05	0.01	99.97
Phycodrys rubens	0.19	0.00	0.05	0.01	99.97
Metridium senile	0.11	0.00	0.05	0.01	99.98
Eulalia viridis	0.15	0.00	0.05	0.01	99.99
Gibbula cineraria	0.15	0.00	0.05	0.00	99.99
Thin flat red algae	0.11	0.00	0.05	0.00	100.00
Chorda filum	0.11	0.00	0.05	0.00	100.00
Cystoclonium purpureum	0.15	0.00	-	0.00	100.00
Bugula plumosa	0.11	0.00	-	0.00	100.00
Buguloidea sp.	0.11	0.00	-	0.00	100.00
Codium fragile	0.11	0.00	-	0.00	100.00
Crepidula fornicata	0.11	0.00	-	0.00	100.00
Ligia oceanica	0.11	0.00	-	0.00	100.00
Petalonia fascia	0.11	0.00	-	0.00	100.00
Polysiphonia elongata	0.11	0.00	-	0.00	100.00
Pterosiphonia parasitica	0.11	0.00	-	0.00	100.00
Scytosiphon lomentaria	0.11	0.00	-	0.00	100.00
Actinia fragacea	0.07	0.00	-	0.00	100.00
Anemonia viridis	0.07	0.00	-	0.00	100.00
Asterias rubens	0.07	0.00	-	0.00	100.00
Brown branched algae	0.07	0.00	-	0.00	100.00
Cerastoderma edule	0.07	0.00	-	0.00	100.00
Chironomidae sp.	0.07	0.00	-	0.00	100.00
Gastroclonium ovatum	0.07	0.00	-	0.00	100.00
Gracilaria gracilis	0.07	0.00	-	0.00	100.00
Molgula sp.	0.07	0.00	-	0.00	100.00
Onchidoris bilamellata	0.07	0.00	-	0.00	100.00
Paguridae sp.	0.07	0.00	-	0.00	100.00
Plocamium cartilagineum	0.07	0.00	-	0.00	100.00
Rhodothamniella floridula	0.07	0.00	-	0.00	100.00
Sagartia elegans	0.07	0.00	-	0.00	100.00
Sagartia troglodytes	0.07	0.00	-	0.00	100.00
Spyridia filamentosa	0.07	0.00	-	0.00	100.00
Aulactinia verrucosa	0.04	0.00	-	0.00	100.00
Balanus perforatus	0.04	0.00	-	0.00	100.00
Cladophora sp.	0.04	0.00	-	0.00	100.00
Necora puber	0.04	0.00	-	0.00	100.00
Polyplacophora sp.	0.04	0.00	-	0.00	100.00
Terebellidae sp.	0.04	0.00	-	0.00	100.00

Table 6 Taxa contributing to similarities among communities within characteristic community Group C1 (SIMPER analyses: Clarke 1993).

Av. abundance: numerical scale reflecting average SACFORN abundances (S = 6, A = 5, C = 4, F = 3, O = 2, R = 1, 0 = Not recorded); %: percent contribution to multivariate similarity; Cum. %: cumulative percent contribution to multivariate similarity; Sim/SD: similarity divided by standard deviation of contributions across all pairs of samples (measure of consistency of contribution)

Average similarity = 51.6

Species	**Av. abundance**	**Av. similarity**	**Sim/ SD**	**%**	**Cum. %**
Ulva sp.	4.14	9.22	4.05	17.87	17.87
Patella vulgata	2.57	5.75	6.15	11.14	29.01
Semibalanus balanoides	3.14	5.57	1.51	10.79	39.80
Actinia equina	2.43	4.69	2.93	9.09	48.89
Fucus vesiculosus	2.29	3.79	1.19	7.35	56.24
Porphyra sp.	2.00	3.78	1.45	7.32	63.56
Austrominius modestus	3.00	3.31	0.59	6.41	69.97
Littorina littorea	2.00	3.26	0.88	6.31	76.28
Fucus sp. juv.	2.14	3.06	1.09	5.94	82.21
Fucus spiralis	1.86	2.03	0.62	3.94	86.15
Nucella lapillus	1.57	1.61	0.61	3.11	89.26
Phorcus lineatus	2.00	1.48	0.39	2.87	92.13
Littorina obtusata	1.43	1.44	0.55	2.78	94.92
Chthamalus sp.	1.14	0.79	0.39	1.53	96.45
Gibbula umbilicalis	0.86	0.46	0.37	0.89	97.34
Sabellaria alveolata	0.86	0.35	0.22	0.68	98.02
Amphipod sp.	0.71	0.24	0.22	0.46	98.48
Littorina saxatilis	0.86	0.24	0.22	0.46	98.94
Hydroid sp.	0.71	0.23	0.22	0.44	99.38
Polysiphonia sp.	0.71	0.21	0.22	0.41	99.79
Ascophyllum nodosum	0.43	0.11	0.22	0.21	100.00
Fucus serratus	0.43	0.00	-	0.00	100.00
Mytilus edulis	0.43	0.00	-	0.00	100.00
Mytilus edulis juv.	0.43	0.00	-	0.00	100.00
Palaemon sp.	0.43	0.00	-	0.00	100.00
Palmaria palmata	0.43	0.00	-	0.00	100.00
Carcinus maenas	0.29	0.00	-	0.00	100.00
Osmundea sp.	0.29	0.00	-	0.00	100.00
Corallina officinalis	0.14	0.00	-	0.00	100.00

Table 7 Taxa contributing to similarities among communities within characteristic community Group C2 (SIMPER analyses: Clarke 1993).

Av. abundance: numerical scale reflecting average SACFORN abundances (S = 6, A = 5, C = 4, F = 3, O = 2, R = 1, 0 = Not recorded); %: percent contribution to multivariate similarity; Cum. %: cumulative percent contribution to multivariate similarity; Sim/SD: similarity divided by standard deviation of contributions across all pairs of samples (measure of consistency of contribution)

Average similarity = 62.4					
Species	**Av. abundance**	**Av. similarity**	**Sim/ SD**	**%**	**Cum. %**
Fucus spiralis	4.89	10.18	3.53	16.32	16.32
Ulva sp.	4.04	7.68	2.46	12.30	28.61
Fucus sp. juv.	3.41	7.19	4.53	11.52	40.13
Austrominius modestus	3.67	6.75	3.20	10.81	50.94
Amphipod sp.	3.26	5.84	2.08	9.35	60.30
Semibalanus balanoides	3.07	5.10	1.77	8.18	68.47
Pelvetia canaliculata	2.81	4.05	1.18	6.49	74.96
Patella vulgata	2.37	3.78	1.47	6.06	81.02
Littorina saxatilis	2.19	2.75	0.93	4.40	85.42
Littorina littorea	1.96	2.18	0.78	3.49	88.91
Catenella caespitosa	1.59	1.42	0.56	2.27	91.18
Porphyra sp.	1.41	1.26	0.56	2.02	93.20
Actinia equina	1.19	1.18	0.60	1.89	95.09
Chthamalus sp.	1.26	1.09	0.55	1.75	96.84
Fucus vesiculosus	1.04	0.66	0.41	1.06	97.90
Littorina obtusata	0.56	0.24	0.28	0.38	98.28
Mytilus edulis	0.56	0.20	0.27	0.31	98.59
Nucella lapillus	0.52	0.17	0.23	0.27	98.87
Portunidae sp.	0.52	0.14	0.19	0.22	99.09
Polysiphonia sp.	0.56	0.13	0.19	0.21	99.30
Anurida maritima	0.52	0.09	0.13	0.15	99.45
Chondrus crispus	0.41	0.08	0.13	0.13	99.58
Melarhaphe neretoides	0.41	0.08	0.13	0.12	99.70
Ascophyllum nodosum	0.37	0.06	0.17	0.09	99.79
Ligia oceanica	0.37	0.05	0.09	0.09	99.87
Ceramium sp.	0.30	0.02	0.05	0.03	99.91
Mytilus edulis juv.	0.15	0.02	0.09	0.03	99.93
Gibbula umbilicalis	0.22	0.02	0.05	0.03	99.96
Lithothamnia	0.26	0.01	0.05	0.02	99.98
Fucus serratus	0.19	0.01	0.05	0.01	99.99
Laurencia obtusa	0.11	0.00	0.05	0.01	100.00
Fucus ceranoides	0.19	0.00	-	0.00	100.00
Idotea granulosa	0.11	0.00	-	0.00	100.00
Mastocarpus stellatus	0.11	0.00	-	0.00	100.00
Cladostephus spongiosus	0.07	0.00	-	0.00	100.00
Osmundea sp.	0.07	0.00	-	0.00	100.00

Chondracanthus acicularis	0.04	0.00	-	0.00	100.00
Palmaria palmata	0.04	0.00	-	0.00	100.00

Table 8 Taxa contributing to similarities among communities within characteristic community Group C3 (SIMPER analyses: Clarke 1993).

Av. abundance: numerical scale reflecting average SACFORN abundances (S = 6, A = 5, C = 4, F = 3, O = 2, R = 1, 0 = Not recorded); %: percent contribution to multivariate similarity; Cum. %: cumulative percent contribution to multivariate similarity; Sim/SD: similarity divided by standard deviation of contributions across all pairs of samples (measure of consistency of contribution)

Average similarity = 62.1					
Species	**Av. abundance**	**Av. similarity**	**Sim/ SD**	**%**	**Cum. %**
Austrominius modestus	4.93	7.82	3.51	12.59	12.59
Ulva sp.	3.90	6.43	3.13	10.36	22.95
Semibalanus balanoides	3.57	5.19	2.53	8.35	31.31
Fucus spiralis	3.37	4.84	3.39	7.79	39.10
Fucus sp. juv.	2.80	4.62	3.68	7.44	46.54
Littorina saxatilis	3.10	4.59	2.10	7.39	53.93
Melarhaphe neretoides	3.13	4.23	1.47	6.81	60.75
Porphyra sp.	2.43	3.56	1.85	5.74	66.48
Littorina littorea	2.90	3.43	1.58	5.53	72.01
Patella vulgata	2.50	2.85	1.18	4.59	76.60
Chthamalus sp.	2.80	2.56	0.80	4.13	80.73
Mytilus edulis	2.53	2.33	0.91	3.75	84.49
Mytilus edulis juv.	2.20	2.13	1.07	3.43	87.92
Nucella lapillus	2.20	1.79	0.79	2.89	90.81
Actinia equina	1.87	1.56	0.82	2.51	93.31
Amphipod sp.	1.77	1.09	0.54	1.76	95.07
Anurida maritima	1.43	0.66	0.42	1.06	96.14
Fucus vesiculosus	1.27	0.65	0.40	1.05	97.19
Ceramium sp.	1.03	0.39	0.34	0.63	97.81
Hydroid sp.	0.90	0.30	0.29	0.48	98.29
Catenella caespitosa	0.77	0.25	0.26	0.40	98.69
Pelvetia canaliculata	0.77	0.24	0.27	0.38	99.07
Portunidae sp.	0.67	0.15	0.19	0.24	99.31
Polysiphonia sp.	0.60	0.13	0.22	0.21	99.52
Sabellaria alveolata	0.60	0.12	0.18	0.19	99.71
Chondrus crispus	0.33	0.04	0.11	0.07	99.78
Ascophyllum nodosum	0.33	0.04	0.10	0.06	99.83
Gibbula umbilicalis	0.27	0.03	0.100	0.05	99.88
Littorina obtusata	0.13	0.03	0.12	0.04	99.93
Idotea granulosa	0.23	0.02	0.08	0.04	99.96
Palaemon sp.	0.23	0.01	0.05	0.02	99.98
Red algal turf	0.13	0.01	0.05	0.01	99.99

Heterosiphonia plumosa	0.13	0.01	0.05	0.01	100.00
Carcinus maenas	0.13	0.00	0.05	0.00	100.00
Brown filamentous algae	0.10	0.00	-	0.00	100.00
Dynamena pumila	0.10	0.00	-	0.00	100.00
Eulalia viridis	0.10	0.00	-	0.00	100.00
Laurencia obtusa	0.10	0.00	-	0.00	100.00
Lithothamnia	0.10	0.00	-	0.00	100.00
Phorcus lineatus	0.10	0.00	-	0.00	100.00
Sagartia troglodytes	0.10	0.00	-	0.00	100.00
Spirorbis sp.	0.10	0.00	-	0.00	100.00
Bryozoa crust orange	0.07	0.00	-	0.00	100.00
Fucus serratus	0.07	0.00	-	0.00	100.00
Ligia oceanica	0.07	0.00	-	0.00	100.00
Mastocarpus stellatus	0.07	0.00	-	0.00	100.00
Cancer pagurus	0.03	0.00	-	0.00	100.00
Cladophora rupestrus	0.03	0.00	-	0.00	100.00
Cladostephus spongiosus	0.03	0.00	-	0.00	100.00
Ocenebra erinacea	0.03	0.00	-	0.00	100.00
Porifera crust orange	0.03	0.00	-	0.00	100.00

Table 9 Taxa contributing to similarities among communities within characteristic community Group D1 (SIMPER analyses: Clarke 1993).

Av. abundance: numerical scale reflecting average SACFORN abundances (S = 6, A = 5, C = 4, F = 3, O = 2, R = 1, 0 = Not recorded); %: percent contribution to multivariate similarity; Cum. %: cumulative percent contribution to multivariate similarity; Sim/SD: similarity divided by standard deviation of contributions across all pairs of samples (measure of consistency of contribution)

Average similarity = 54.4					
Species	**Av. abundance**	**Av. similarity**	**Sim/ SD**	**%**	**Cum. %**
Semibalanus balanoides	5.00	3.99	4.91	7.34	7.34
Patella vulgata	4.50	3.55	4.98	6.53	13.87
Chthamalus sp.	4.36	3.39	2.98	6.23	20.10
Ulva sp.	3.93	2.93	3.87	5.38	25.48
Littorina saxatilis	3.57	2.86	5.93	5.26	30.74
Fucus sp. juv.	3.00	2.33	4.31	4.28	35.02
Littorina littorea	2.93	2.13	1.90	3.91	38.93
Ceramium sp.	2.93	1.75	1.59	3.21	42.14
Chondrus crispus	2.79	1.71	1.33	3.14	45.28
Fucus serratus	2.86	1.66	1.40	3.06	48.34
Fucus spiralis	2.64	1.63	1.73	3.00	51.34
Actinia equina	2.64	1.57	1.41	2.89	54.22
Melarhaphe neretoides	2.57	1.54	1.14	2.82	57.05
Lithothamnia	2.79	1.39	1.04	2.56	59.61
Nucella lapillus	2.50	1.39	1.35	2.55	62.16

Polysiphonia sp.	2.50	1.37	1.16	2.53	64.68
Fucus vesiculosus	2.57	1.36	1.20	2.49	67.18
Austrominius modestus	2.43	1.20	1.14	2.20	69.38
Gibbula umbilicalis	2.29	1.14	0.86	2.10	71.49
Littorina obtusata	2.07	0.97	0.93	1.79	73.27
Porphyra sp.	1.93	0.81	0.86	1.50	74.77
Bryozoa crust white	1.71	0.80	0.78	1.47	76.24
Catenella caespitosa	1.86	0.78	0.77	1.44	77.67
Porifera crust orange	1.64	0.78	0.77	1.43	79.10
Corallina officinalis	1.86	0.75	0.74	1.37	80.48
Mytilus edulis juv.	1.64	0.71	0.76	1.30	81.78
Lomentaria articulata	1.64	0.69	0.72	1.27	83.05
Palmaria palmata	2.00	0.68	0.72	1.26	84.31
Cladostephus spongiosus	1.43	0.67	0.63	1.24	85.55
Hydroid sp.	1.71	0.58	0.52	1.06	86.61
Phorcus lineatus	1.64	0.55	0.49	1.02	87.63
Porifera crust yellow	1.36	0.54	0.65	0.99	88.61
Sabellaria alveolata	1.64	0.51	0.49	0.93	89.55
Amphipod sp.	1.29	0.48	0.52	0.89	90.43
Spirobranchus sp.	1.36	0.46	0.52	0.85	91.28
Ascophyllum nodosum	1.43	0.43	0.61	0.79	92.08
Mastocarpus stellatus	1.50	0.41	0.44	0.76	92.84
Portunidae sp.	1.43	0.37	0.44	0.69	93.52
Mytilus edulis	0.93	0.29	0.60	0.53	94.05
Idotea granulosa	1.00	0.28	0.33	0.51	94.56
Pelvetia canaliculata	0.93	0.27	0.51	0.50	95.07
Osmundea osmundea	1.21	0.26	0.33	0.48	95.54
Osmundea sp.	1.36	0.25	0.31	0.47	96.01
Spirorbis sp.	1.21	0.24	0.34	0.43	96.44
Membranoptera alata	1.07	0.23	0.42	0.42	96.86
Cladophora rupestrus	0.93	0.22	0.43	0.41	97.27
Bryozoa crust orange	1.07	0.20	0.33	0.36	97.64
Laminaria digitata	1.14	0.16	0.26	0.29	97.93
Alcyonidium sp.	0.93	0.16	0.32	0.29	98.22
Dynamena pumila	0.86	0.15	0.26	0.28	98.50
Patella depressa	0.57	0.14	0.26	0.25	98.75
Leathesia difformis	0.71	0.11	0.26	0.20	98.95
Laurencia obtusa	0.79	0.10	0.18	0.19	99.14
Red algal turf	0.57	0.10	0.25	0.18	99.32
Bowerbankia sp.	0.71	0.09	0.18	0.16	99.48
Heterosiphonia plumosa	0.64	0.06	0.18	0.12	99.60
Chondracanthus acicularis	0.57	0.04	0.10	0.08	99.67
Rhodomela confervoides	0.57	0.03	0.10	0.05	99.72
Rhizoclonium riparium	0.43	0.02	0.10	0.05	99.77
Saccharina latissima	0.43	0.02	0.10	0.04	99.81
Hydrallmania falcata	0.43	0.02	0.10	0.03	99.84

Lanice conchilega	0.43	0.02	0.10	0.03	99.87
Brown jelly algae	0.29	0.02	0.10	0.03	99.90
Anurida maritima	0.43	0.02	0.10	0.03	99.93
Phycodrys rubens	0.36	0.01	0.10	0.02	99.95
Eulalia viridis	0.29	0.01	0.10	0.02	99.97
Red crinkly algae	0.21	0.01	0.10	0.01	99.99
Chorda filum	0.21	0.01	0.10	0.01	100.00
Cystoclonium purpureum	0.29	0.00	-	0.00	100.00
Bugula plumosa	0.21	0.00	-	0.00	100.00
Buguloidea sp.	0.21	0.00	-	0.00	100.00
Ligia oceanica	0.21	0.00	-	0.00	100.00
Polysiphonia elongata	0.21	0.00	-	0.00	100.00
Scytosiphon lomentaria	0.21	0.00	-	0.00	100.00
Actinia fragacea	0.14	0.00	-	0.00	100.00
Anemonia viridis	0.14	0.00	-	0.00	100.00
Asterias rubens	0.14	0.00	-	0.00	100.00
Brown branched algae	0.14	0.00	-	0.00	100.00
Carcinus maenas	0.14	0.00	-	0.00	100.00
Chironomidae sp. juv.	0.14	0.00	-	0.00	100.00
Fish	0.14	0.00	-	0.00	100.00
Gastroclonium ovatum	0.14	0.00	-	0.00	100.00
Gracilaria gracilis	0.14	0.00	-	0.00	100.00
Molgula sp.	0.14	0.00	-	0.00	100.00
Onchidoris bilamellata	0.14	0.00	-	0.00	100.00
Plocamium cartilagineum	0.14	0.00	-	0.00	100.00
Sagartia elegans	0.14	0.00	-	0.00	100.00
Sagartia troglodytes	0.14	0.00	-	0.00	100.00
Spyridia filamentosa	0.14	0.00	-	0.00	100.00
Aulactinia verrucosa	0.07	0.00	-	0.00	100.00
Balanus perforatus	0.07	0.00	-	0.00	100.00
Cladophora sp.	0.07	0.00	-	0.00	100.00
Gibbula cineraria	0.07	0.00	-	0.00	100.00
Metridium senile	0.07	0.00	-	0.00	100.00
Necora puber	0.07	0.00	-	0.00	100.00
Polyplacophora sp.	0.07	0.00	-	0.00	100.00
Terebellidae sp.	0.07	0.00	-	0.00	100.00

Table 10 Taxa contributing to similarities among communities within characteristic community Group D2 (SIMPER analyses: Clarke 1993).

Av. abundance: numerical scale reflecting average SACFORN abundances (S = 6, A = 5, C = 4, F = 3, O = 2, R = 1, 0 = Not recorded); %: percent contribution to multivariate similarity; Cum. %: cumulative percent contribution to multivariate similarity; Sim/SD: similarity divided by standard deviation of contributions across all pairs of samples (measure of consistency of contribution)

Average similarity = 52.3

Species	Av. abundance	Av. similarity	Sim/SD	%	Cum. %
Ulva sp.	4.62	6.46	4.97	12.35	12.35
Semibalanus balanoides	4.46	5.98	4.15	11.43	23.79
Patella vulgata	3.46	4.82	5.61	9.23	33.02
Fucus sp. juv.	2.92	3.51	1.98	6.71	39.72
Littorina littorea	3.00	3.42	1.61	6.54	46.26
Porphyra sp.	2.92	3.24	1.83	6.21	52.47
Chondrus crispus	2.85	3.14	1.42	6.01	58.48
Nucella lapillus	2.62	3.08	1.46	5.89	64.37
Fucus vesiculosus	2.85	2.73	1.08	5.23	69.59
Fucus serratus	2.77	2.60	1.23	4.98	74.57
Actinia equina	2.38	2.38	1.09	4.55	79.12
Mastocarpus stellatus	2.38	1.84	0.87	3.51	82.64
Fucus spiralis	2.31	1.54	0.68	2.95	85.59
Austrominius modestus	1.92	1.45	0.72	2.77	88.36
Ceramium sp.	1.62	0.87	0.48	1.66	90.02
Portunidae sp.	1.31	0.70	0.52	1.34	91.36
Chthamalus sp.	1.38	0.54	0.45	1.03	92.40
Sabellaria alveolata	1.15	0.46	0.36	0.88	93.28
Littorina obtusata	1.15	0.37	0.34	0.70	93.98
Littorina saxatilis	1.15	0.37	0.32	0.70	94.68
Dynamena pumila	1.00	0.35	0.29	0.68	95.36
Lithothamnia	1.00	0.35	0.37	0.67	96.02
Mytilus edulis	1.00	0.33	0.31	0.62	96.64
Palmaria palmata	1.00	0.28	0.34	0.53	97.18
Fucus ceranoides	1.23	0.25	0.20	0.47	97.65
Cladostephus spongiosus	0.85	0.23	0.26	0.44	98.09
Catenella caespitosa	0.69	0.23	0.29	0.43	98.52
Amphipod sp.	0.85	0.22	0.20	0.43	98.95
Gibbula umbilicalis	0.69	0.14	0.19	0.27	99.22
Polysiphonia sp.	0.54	0.06	0.11	0.12	99.34
Spirorbis sp.	0.54	0.05	0.11	0.10	99.45
Lomentaria articulata	0.62	0.05	0.11	0.10	99.55
Brown filamentous algae	0.38	0.04	0.11	0.08	99.62
Ascophyllum nodosum	0.38	0.04	0.11	0.07	99.69
Bryozoa crust white	0.38	0.04	0.11	0.07	99.76
Carcinus maenas	0.46	0.03	0.11	0.07	99.83

Spirobranchus sp.	0.38	0.03	0.11	0.06	99.89
Melarhaphe neretoides	0.62	0.03	0.11	0.05	99.94
Phorcus lineatus	0.23	0.02	0.11	0.03	99.97
Porifera crust orange	0.15	0.01	0.11	0.03	100.00
Lanice conchilega	0.46	0.00	-	0.00	100.00
Corallina officinalis	0.38	0.00	-	0.00	100.00
Cladophora rupestrus	0.23	0.00	-	0.00	100.00
Codium fragile	0.23	0.00	-	0.00	100.00
Crepidula fornicata	0.23	0.00	-	0.00	100.00
Gibbula cineraria	0.23	0.00	-	0.00	100.00
Laminaria digitata	0.23	0.00	-	0.00	100.00
Petalonia fascia	0.23	0.00	-	0.00	100.00
Pterosiphonia parasitica	0.23	0.00	-	0.00	100.00
Red algal turf	0.23	0.00	-	0.00	100.00
Rhizoclonium riparium	0.23	0.00	-	0.00	100.00
Cerastoderma edule	0.15	0.00	-	0.00	100.00
Fish	0.15	0.00	-	0.00	100.00
Metridium senile	0.15	0.00	-	0.00	100.00
Mytilus edulis juv.	0.15	0.00	-	0.00	100.00
Osmundea sp.	0.15	0.00	-	0.00	100.00
Paguridae sp.	0.15	0.00	-	0.00	100.00
Patella depressa	0.15	0.00	-	0.00	100.00
Rhodothamniella floridula	0.15	0.00	-	0.00	100.00
Pelvetia canaliculata	0.08	0.00	-	0.00	100.00

Table 11 Taxa contributing to similarities among communities within characteristic community Group B1 (SIMPER analyses: Clarke 1993).

Av. abundance: numerical scale reflecting average SACFORN abundances (S = 6, A = 5, C = 4, F = 3, O = 2, R = 1, 0 = Not recorded); %: percent contribution to multivariate similarity; Cum. %: cumulative percent contribution to multivariate similarity; Sim/SD: similarity divided by standard deviation of contributions across all pairs of samples (measure of consistency of contribution)

Average similarity = 61.1

Species	**Av. abundance**	**Av. similarity**	**Sim/ SD**	**%**	**Cum. %**
Fucus spiralis	4.93	4.74	5.96	7.75	7.75
Austrominius modestus	4.47	3.98	3.38	6.52	14.27
Fucus sp. juv.	3.80	3.54	4.20	5.78	20.05
Semibalanus balanoides	3.93	3.35	3.92	5.48	25.53
Littorina littorea	3.73	3.24	3.77	5.30	30.83
Ulva sp.	3.67	3.21	3.80	5.25	36.08
Amphipod sp.	3.80	3.09	2.00	5.05	41.13
Ascophyllum nodosum	4.00	2.85	1.24	4.66	45.80
Catenella caespitosa	3.47	2.64	1.55	4.32	50.11
Fucus vesiculosus	3.33	2.61	1.92	4.27	54.39
Littorina obtusata	3.00	2.53	2.20	4.14	58.52
Patella vulgata	3.13	2.44	1.60	4.00	62.52
Pelvetia canaliculata	3.40	2.36	1.19	3.86	66.38
Littorina saxatilis	2.60	1.82	1.25	2.98	69.35
Polysiphonia sp.	2.60	1.74	1.00	2.84	72.19
Actinia equina	2.33	1.71	1.40	2.80	75.00
Mytilus edulis	2.47	1.66	1.22	2.71	77.71
Anurida maritima	2.60	1.54	0.83	2.52	80.23
Ceramium sp.	2.53	1.45	0.85	2.37	82.59
Lithothamnia	2.27	1.15	0.71	1.89	84.48
Nucella lapillus	2.07	1.10	0.79	1.79	86.28
Fucus serratus	2.20	1.01	0.77	1.66	87.94
Chondrus crispus	1.87	0.94	0.79	1.54	89.48
Portunidae sp.	1.80	0.92	0.78	1.51	90.98
Porphyra sp.	1.60	0.90	0.95	1.47	92.45
Chthamalus sp.	1.73	0.82	0.73	1.34	93.79
Melarhaphe neretoides	1.47	0.52	0.46	0.85	94.64
Carcinus maenas	1.27	0.42	0.39	0.68	95.32
Hydroid sp.	1.20	0.42	0.40	0.68	96.01
Mytilus edulis juv.	1.13	0.40	0.39	0.65	96.66
Cladophora rupestrus	1.00	0.30	0.39	0.49	97.15
Red algal turf	1.13	0.29	0.38	0.47	97.62
Alcyonidium sp.	0.93	0.24	0.32	0.39	98.00
Dynamena pumila	1.00	0.22	0.32	0.37	98.37
Lomentaria articulata	1.00	0.20	0.28	0.32	98.69
Cladostephus spongiosus	0.67	0.11	0.24	0.18	98.88

Gibbula umbilicalis	0.60	0.09	0.22	0.15	99.03
Idotea granulosa	0.60	0.08	0.17	0.14	99.16
Brown filamentous algae	0.60	0.07	0.17	0.11	99.28
Bryozoa crust white	0.53	0.07	0.17	0.11	99.38
Mastocarpus stellatus	0.53	0.06	0.17	0.10	99.49
Rhizoclonium riparium	0.47	0.05	0.17	0.09	99.57
Ligia oceanica	0.53	0.05	0.15	0.08	99.65
Fucus ceranoides	0.53	0.03	0.10	0.06	99.71
Porifera crust orange	0.33	0.03	0.17	0.04	99.75
Spirobranchus sp.	0.40	0.03	0.10	0.04	99.79
Spirorbis sp.	0.47	0.03	0.10	0.04	99.84
Palaemon sp.	0.60	0.03	0.10	0.04	99.88
Palmaria palmata	0.20	0.03	0.17	0.04	99.92
Phorcus lineatus	0.33	0.02	0.10	0.04	99.96
Fish sp.	0.40	0.02	0.10	0.03	99.98
Corallina officinalis	0.27	0.01	0.10	0.02	100.00
Bryozoa crust orange	0.20	0.00	-	0.00	100.00
Cerastoderma edule	0.20	0.00	-	0.00	100.00
Chondracanthus acicularis	0.20	0.00	-	0.00	100.00
Osmundea osmundea	0.20	0.00	-	0.00	100.00
Polysiphonia lanosa	0.20	0.00	-	0.00	100.00
Brown encrusting algae	0.13	0.00	-	0.00	100.00
Cladophora sp.	0.13	0.00	-	0.00	100.00
Laurencia obtusa	0.13	0.00	-	0.00	100.00
Osmundea sp.	0.13	0.00	-	0.00	100.00
Pterosiphonia parasitica	0.13	0.00	-	0.00	100.00
Anemone sp.	0.07	0.00	-	0.00	100.00
Brown jelly algae	0.07	0.00	-	0.00	100.00
Chorda filum	0.07	0.00	-	0.00	100.00
Laminaria digitata	0.07	0.00	-	0.00	100.00
Leathesia difformis	0.07	0.00	-	0.00	100.00
Sabellaria alveolata	0.07	0.00	-	0.00	100.00

Table 12 Taxa contributing to similarities among communities within characteristic community Group B2 (SIMPER analyses: Clarke 1993).

Av. abundance: numerical scale reflecting average SACFORN abundances (S = 6, A = 5, C = 4, F = 3, O = 2, R = 1, 0 = Not recorded); %: percent contribution to multivariate similarity; Cum. %: cumulative percent contribution to multivariate similarity; Sim/SD: similarity divided by standard deviation of contributions across all pairs of samples (measure of consistency of contribution)

Average similarity = 57.3					
Species	**Av. abundance**	**Av. similarity**	**Sim/ SD**	**%**	**Cum. %**
Ascophyllum nodosum	5.25	8.40	5.22	14.65	14.65
Fucus spiralis	4.75	6.97	2.79	12.15	26.80
Catenella caespitosa	4.25	6.84	5.15	11.94	38.74
Pelvetia canaliculata	4.00	6.31	5.68	11.00	49.74
Ulva sp.	3.25	5.38	7.68	9.39	59.13
Fucus sp. juv.	2.88	4.47	4.95	7.79	66.92
Ceramium sp.	3.13	2.70	0.73	4.71	71.64
Cladophora rupestrus	2.63	2.67	0.98	4.66	76.30
Semibalanus balanoides	2.00	2.16	1.00	3.76	80.06
Amphipod sp.	2.38	2.03	0.72	3.54	83.60
Austrominius modestus	1.50	1.26	0.72	2.19	85.79
Dynamena pumila	1.50	1.10	0.51	1.92	87.71
Fucus vesiculosus	1.88	1.06	0.53	1.85	89.56
Lithothamnia	1.38	0.77	0.50	1.34	90.90
Chondrus crispus	1.25	0.75	0.51	1.31	92.21
Littorina obtusata	1.00	0.72	0.51	1.26	93.47
Patella vulgata	1.38	0.70	0.51	1.21	94.68
Polysiphonia sp.	1.38	0.59	0.34	1.03	95.71
Littorina littorea	1.00	0.46	0.46	0.80	96.51
Littorina saxatilis	1.00	0.43	0.33	0.74	97.26
Mytilus edulis	1.00	0.38	0.34	0.66	97.92
Carcinus maenas	1.00	0.30	0.28	0.52	98.44
Portunidae sp.	0.75	0.28	0.32	0.49	98.93
Chthamalus sp.	1.00	0.24	0.32	0.42	99.35
Mastocarpus stellatus	0.75	0.12	0.19	0.21	99.56
Fucus serratus	0.63	0.12	0.19	0.21	99.77
Nucella lapillus	0.25	0.07	0.19	0.12	99.89
Porphyra sp.	0.38	0.06	0.19	0.11	100.00
Fucus ceranoides	0.63	0.00	-	0.00	100.00
Rhodothamniella floridula	0.63	0.00	-	0.00	100.00
Ligia oceanica	0.50	0.00	-	0.00	100.00
Alcyonidium sp.	0.38	0.00	-	0.00	100.00
Idotea granulosa	0.38	0.00	-	0.00	100.00
Actinia equina	0.25	0.00	-	0.00	100.00
Gibbula umbilicalis	0.25	0.00	-	0.00	100.00
Osmundea sp.	0.25	0.00	-	0.00	100.00

Red encrusting algae	0.25	0.00	-	0.00	100.00
Mytilus edulis juv.	0.13	0.00	-	0.00	100.00

Table 13 Taxa contributing to similarities among communities within characteristic community Group C1.1 (SIMPER analyses: Clarke 1993).

Av. abundance: numerical scale reflecting average SACFORN abundances (S = 6, A = 5, C = 4, F = 3, O = 2, R = 1, 0 = Not recorded); %: percent contribution to multivariate similarity; Cum. %: cumulative percent contribution to multivariate similarity; Sim/SD: similarity divided by standard deviation of contributions across all pairs of samples (measure of consistency of contribution)

Average similarity = 58.8					
Species	**Av. abundance**	**Av. similarity**	**Sim/ SD**	**%**	**Cum. %**
Austrominius modestus	5.25	11.57	3.73	19.69	19.69
Ulva sp.	4.25	9.82	3.43	16.71	36.40
Semibalanus balanoides	4.00	8.37	8.92	14.24	50.64
Patella vulgata	2.75	6.51	8.59	11.08	61.72
Porphyra sp.	2.50	5.80	3.72	9.87	71.60
Actinia equina	2.75	5.72	6.07	9.73	81.33
Nucella lapillus	2.25	3.18	0.90	5.41	86.74
Fucus vesiculosus	1.75	2.32	0.69	3.94	90.68
Littorina littorea	1.50	1.47	0.41	2.50	93.18
Sabellaria alveolata	1.50	1.22	0.41	2.07	95.26
Fucus sp. juv.	1.50	1.20	0.91	2.04	97.30
Gibbula umbilicalis	1.25	0.79	0.41	1.35	98.65
Hydroid sp.	1.25	0.79	0.41	1.35	100.00
Fucus spiralis	0.75	0.00	-	0.00	100.00
Mytilus edulis	0.75	0.00	-	0.00	100.00
Mytilus edulis juv.	0.75	0.00	-	0.00	100.00
Palaemon sp.	0.75	0.00	-	0.00	100.00
Palmaria palmata	0.75	0.00	-	0.00	100.00
Polysiphonia sp.	0.75	0.00	-	0.00	100.00
Osmundea sp.	0.50	0.00	-	0.00	100.00
Ascophyllum nodosum	0.25	0.00	-	0.00	100.00
Littorina obtusata	0.25	0.00	-	0.00	100.00

Table 14 Taxa contributing to similarities among communities within characteristic community Group C1.2 (SIMPER analyses: Clarke 1993).

Av. abundance: numerical scale reflecting average SACFORN abundances (S = 6, A = 5, C = 4, F = 3, O = 2, R = 1, 0 = Not recorded); %: percent contribution to multivariate similarity; Cum. %: cumulative percent contribution to multivariate similarity; Sim/SD: similarity divided by standard deviation of contributions across all pairs of samples (measure of consistency of contribution)

Average similarity = 71.6					
Species	**Av. abundance**	**Av. similarity**	**Sim/ SD**	**%**	**Cum. %**
Phorcus lineatus	4.67	10.37	5.62	14.49	14.49
Ulva sp.	4.00	7.93	6.50	11.08	25.56
Fucus sp. juv.	3.00	7.15	23.67	9.99	35.55
Fucus spiralis	3.33	7.15	23.67	9.99	45.55
Littorina obtusata	3.00	7.15	23.67	9.99	55.54
Littorina littorea	2.67	5.60	3.41	7.83	63.36
Chthamalus sp.	2.67	5.54	4.42	7.74	71.11
Fucus vesiculosus	3.00	5.54	4.42	7.74	78.85
Patella vulgata	2.33	4.77	23.67	6.66	85.51
Actinia equina	2.00	3.16	2.44	4.41	89.93
Semibalanus balanoides	2.00	2.33	0.58	3.25	93.18
Amphipod sp.	1.67	1.67	0.58	2.33	95.51
Littorina saxatilis	2.00	1.67	0.58	2.33	97.83
Porphyra sp.	1.33	1.55	0.58	2.17	100.00
Fucus serratus	1.00	0.00	-	0.00	100.00
Ascophyllum nodosum	0.67	0.00	-	0.00	100.00
Carcinus maenas	0.67	0.00	-	0.00	100.00
Nucella lapillus	0.67	0.00	-	0.00	100.00
Polysiphonia sp.	0.67	0.00	-	0.00	100.00
Corallina officinalis	0.33	0.00	-	0.00	100.00
Gibbula umbilicalis	0.33	0.00	-	0.00	100.00

Table 15 Taxa contributing to similarities among communities within characteristic community Group D1.1 (SIMPER analyses: Clarke 1993).

Av. abundance: numerical scale reflecting average SACFORN abundances (S = 6, A = 5, C = 4, F = 3, O = 2, R = 1, 0 = Not recorded); %: percent contribution to multivariate similarity; Cum. %: cumulative percent contribution to multivariate similarity; Sim/SD: similarity divided by standard deviation of contributions across all pairs of samples (measure of consistency of contribution)

Average similarity = 60.4					
Species	**Av. abundance**	**Av. similarity**	**Sim/ SD**	**%**	**Cum. %**
Chthamalus sp.	5.33	4.52	5.53	7.48	7.48
Semibalanus balanoides	5.17	4.41	5.39	7.30	14.78
Ulva sp.	4.50	3.60	4.31	5.96	20.74
Patella vulgata	4.00	3.17	8.79	5.26	26.00
Littorina saxatilis	3.67	2.97	5.98	4.92	30.92
Melarhaphe neretoides	3.67	2.97	5.98	4.92	35.84
Sabellaria alveolata	3.67	2.67	4.32	4.42	40.26
Littorina littorea	3.17	2.57	3.44	4.25	44.51
Hydroid sp.	3.33	2.56	3.68	4.24	48.74
Mytilus edulis juv.	3.17	2.52	4.59	4.17	52.91
Fucus sp. juv.	3.00	2.49	4.03	4.13	57.04
Austrominius modestus	3.67	2.27	1.71	3.75	60.79
Spirobranchus sp.	2.83	2.22	4.75	3.67	64.46
Fucus spiralis	3.17	2.13	3.06	3.52	67.98
Actinia equina	3.17	2.00	2.37	3.31	71.30
Porphyra sp.	3.17	1.92	1.88	3.17	74.47
Fucus vesiculosus	3.00	1.85	1.80	3.06	77.53
Nucella lapillus	3.00	1.61	1.21	2.67	80.20
Polysiphonia sp.	2.50	1.54	1.27	2.55	82.75
Bryozoa crust white	2.17	1.35	1.31	2.23	84.98
Ceramium sp.	2.17	1.07	1.15	1.77	86.75
Littorina obtusata	1.33	0.83	0.78	1.37	88.11
Patella depressa	1.33	0.83	0.78	1.37	89.48
Mytilus edulis	1.67	0.79	1.13	1.31	90.79
Fucus serratus	2.00	0.67	0.69	1.11	91.90
Chondrus crispus	1.67	0.58	0.70	0.96	92.86
Bowerbankia sp.	1.67	0.54	0.48	0.89	93.75
Bryozoa crust orange	1.83	0.53	0.48	0.88	94.63
Idotea granulosa	1.33	0.52	0.46	0.85	95.49
Palmaria palmata	1.83	0.42	0.46	0.69	96.17
Gibbula umbilicalis	1.33	0.40	0.47	0.66	96.84
Corallina officinalis	1.17	0.28	0.43	0.46	97.29
Lithothamnia	1.00	0.23	0.47	0.37	97.67
Portunidae sp.	1.33	0.20	0.26	0.33	98.00
Alcyonidium sp.	1.17	0.15	0.26	0.25	98.25
Dynamena pumila	1.00	0.15	0.26	0.25	98.50

Cladostephus spongiosus	0.83	0.14	0.26	0.23	98.72
Amphipod sp.	0.67	0.14	0.26	0.22	98.95
Hydrallmania falcata	1.00	0.10	0.26	0.17	99.12
Lanice conchilega	1.00	0.10	0.26	0.17	99.28
Anurida maritima	1.00	0.10	0.26	0.16	99.45
Catenella caespitosa	1.00	0.10	0.26	0.16	99.61
Porifera crust orange	0.67	0.10	0.26	0.16	99.78
Membranoptera alata	0.50	0.07	0.26	0.11	99.89
Pelvetia canaliculata	0.67	0.07	0.26	0.11	100.00
Osmundea sp.	1.00	0.00	-	0.00	100.00
Laminaria digitate	0.67	0.00	-	0.00	100.00
Bugula plumosa	0.50	0.00	-	0.00	100.00
Buguloidea sp.	0.50	0.00	-	0.00	100.00
Eulalia viridis	0.50	0.00	-	0.00	100.00
Lomentaria articulata	0.50	0.00	-	0.00	100.00
Actinia fragacea	0.33	0.00	-	0.00	100.00
Asterias rubens	0.33	0.00	-	0.00	100.00
Carcinus maenas	0.33	0.00	-	0.00	100.00
Chironomidae sp. juv.	0.33	0.00	-	0.00	100.00
Fish	0.33	0.00	-	0.00	100.00
Gracilaria gracilis	0.33	0.00	-	0.00	100.00
Molgula sp.	0.33	0.00	-	0.00	100.00
Onchidoris bilamellata	0.33	0.00	-	0.00	100.00
Osmundea osmundea	0.33	0.00	-	0.00	100.00
Porifera crust yellow	0.33	0.00	-	0.00	100.00
Sagartia troglodytes	0.33	0.00	-	0.00	100.00
Ascophyllum nodosum	0.17	0.00	-	0.00	100.00
Chorda filum	0.17	0.00	-	0.00	100.00
Cladophora rupestrus	0.17	0.00	-	0.00	100.00
Gibbula cineraria	0.17	0.00	-	0.00	100.00
Metridium senile	0.17	0.00	-	0.00	100.00
Phorcus lineatus	0.17	0.00	-	0.00	100.00
Red crinkly algae	0.17	0.00	-	0.00	100.00
Red algal turf	0.17	0.00	-	0.00	100.00
Terebellidae sp.	0.17	0.00	-	0.00	100.00

Table 16 Taxa contributing to similarities among communities within characteristic community Group D1.2 (SIMPER analyses: Clarke 1993).

Av. abundance: numerical scale reflecting average SACFORN abundances (S = 6, A = 5, C = 4, F = 3, O = 2, R = 1, 0 = Not recorded); %: percent contribution to multivariate similarity; Cum. %: cumulative percent contribution to multivariate similarity; Sim/SD: similarity divided by standard deviation of contributions across all pairs of samples (this is a measure of consistency of contribution across replicates)

Average similarity = 61.5

Species	Av. abundance	Av. similarity	Sim/ SD	%	Cum. %
Patella vulgata	4.88	3.90	4.63	6.35	6.35
Semibalanus balanoides	4.88	3.64	5.18	5.92	12.27
Lithothamnia	4.13	2.94	4.71	4.79	17.05
Chthamalus sp.	3.63	2.91	2.60	4.73	21.78
Chondrus crispus	3.63	2.87	5.03	4.66	26.44
Littorina saxatilis	3.50	2.73	6.55	4.44	30.88
Fucus serratus	3.50	2.60	4.99	4.22	35.11
Ulva sp.	3.50	2.50	4.60	4.06	39.17
Ceramium sp.	3.50	2.31	2.31	3.76	42.93
Fucus sp. juv.	3.00	2.16	5.21	3.52	46.45
Gibbula umbilicalis	3.00	1.90	1.29	3.09	49.54
Littorina littorea	2.75	1.75	1.47	2.85	52.39
Lomentaria articulata	2.50	1.67	2.52	2.72	55.11
Porifera crust orange	2.38	1.65	1.59	2.69	57.80
Phorcus lineatus	2.75	1.59	1.01	2.58	60.38
Catenella caespitosa	2.50	1.54	1.54	2.50	62.88
Mastocarpus stellatus	2.63	1.34	1.04	2.18	65.07
Porifera crust yellow	2.13	1.32	1.63	2.15	67.21
Actinia equina	2.25	1.24	1.02	2.02	69.23
Fucus spiralis	2.25	1.23	1.38	2.00	71.23
Nucella lapillus	2.13	1.22	1.37	1.98	73.21
Polysiphonia sp.	2.50	1.18	1.01	1.93	75.13
Littorina obtusata	2.63	1.18	0.97	1.92	77.05
Ascophyllum nodosum	2.38	1.15	1.44	1.87	78.91
Corallina officinalis	2.38	1.14	1.00	1.85	80.76
Cladostephus spongiosus	1.88	1.13	1.00	1.84	82.61
Fucus vesiculosus	2.25	0.94	0.93	1.53	84.14
Amphipod sp.	1.75	0.82	0.69	1.33	85.47
Palmaria palmata	2.13	0.79	0.93	1.29	86.76
Spirorbis sp.	2.13	0.77	0.69	1.24	88.01
Melarhaphe neretoides	1.75	0.75	0.70	1.21	89.22
Austrominius modestus	1.50	0.67	0.96	1.09	90.30
Osmundea osmundea	1.88	0.60	0.49	0.98	91.28
Cladophora rupestrus	1.50	0.55	0.72	0.90	92.18
Osmundea sp.	1.63	0.47	0.43	0.77	92.96

Portunidae sp.	1.50	0.47	0.51	0.76	93.71
Bryozoa crust white	1.38	0.42	0.50	0.68	94.39
Pelvetia canaliculata	1.13	0.40	0.69	0.65	95.04
Membranoptera alata	1.50	0.36	0.51	0.59	95.62
Leathesia difformis	1.25	0.36	0.49	0.58	96.21
Laurencia obtusa	1.38	0.33	0.33	0.54	96.75
Porphyra sp.	1.00	0.32	0.51	0.52	97.27
Laminaria digitate	1.50	0.23	0.34	0.37	97.64
Heterosiphonia plumosa	1.13	0.21	0.34	0.34	97.98
Red algal turf	0.88	0.20	0.34	0.32	98.29
Mytilus edulis juv.	0.50	0.18	0.51	0.30	98.59
Chondracanthus acicularis	1.00	0.14	0.19	0.22	98.81
Alcyonidium sp.	0.75	0.11	0.31	0.17	98.98
Rhodomela confervoides	1.00	0.09	0.19	0.14	99.13
Idotea granulosa	0.75	0.08	0.19	0.14	99.26
Dynamena pumila	0.75	0.08	0.19	0.14	99.40
Rhizoclonium riparium	0.75	0.08	0.19	0.13	99.53
Mytilus edulis	0.38	0.08	0.34	0.13	99.66
Saccharina latissima	0.75	0.07	0.19	0.11	99.76
Brown jelly algae	0.50	0.05	0.19	0.09	99.85
Bryozoa crust orange	0.50	0.05	0.19	0.08	99.93
Phycodrys rubens	0.63	0.04	0.19	0.07	100.00
Cystoclonium purpureum	0.50	0.00	-	0.00	100.00
Hydroid sp.	0.50	0.00	-	0.00	100.00
Ligia oceanica	0.38	0.00	-	0.00	100.00
Polysiphonia elongata	0.38	0.00	-	0.00	100.00
Scytosiphon lomentaria	0.38	0.00	-	0.00	100.00
Anemonia viridis	0.25	0.00	-	0.00	100.00
Brown branched algae	0.25	0.00	-	0.00	100.00
Chorda filum	0.25	0.00	-	0.00	100.00
Gastroclonium ovatum	0.25	0.00	-	0.00	100.00
Plocamium cartilagineum	0.25	0.00	-	0.00	100.00
Red crinkly algae	0.25	0.00	-	0.00	100.00
Sagartia elegans	0.25	0.00	-	0.00	100.00
Spirobranchus sp.	0.25	0.00	-	0.00	100.00
Spyridia filamentosa	0.25	0.00	-	0.00	100.00
Aulactinia verrucosa	0.13	0.00	-	0.00	100.00
Balanus perforatus	0.13	0.00	-	0.00	100.00
Cladophora sp.	0.13	0.00	-	0.00	100.00
Eulalia viridis	0.13	0.00	-	0.00	100.00
Necora puber	0.13	0.00	-	0.00	100.00
Polyplacophora sp.	0.13	0.00	-	0.00	100.00
Sabellaria alveolata	0.13	0.00	-	0.00	100.00

APPENDIX IV

Supplementary information regarding GPP estimation in artificial and natural rock pools

Supplementary information regarding gross primary productivity estimation in artificial and natural rock pools

Determining optimal dark and light period durations

In order to make reliable comparisons of ecosystem functioning between rock pool communities, and to avoid underestimating photosynthetic activity, Noël et al. (2010) reported that net primary productivity (NPP) and community respiration (R) must be measured: (i) during the linear phase of gas exchange processes; and (ii) before rock pool water reaches supersaturation. Through field and laboratory trials, they found that the rate of respiration was linear throughout dark periods (up to 2 hours), but that a minimum ten-minute stabilising period was necessary before a constant rate of change was recorded. They also recommended a ten-minute stabilising period before measuring photosynthetic rate during light periods, but warned that supersaturation can occur rapidly in small pools or in pools with high algal biomass (e.g. in 15-30 minutes).

We carried out a preliminary trial in one of the ‘deep’ (i.e. 15 cm diameter, 12 cm deep) natural rock pools at Aberystwyth to determine appropriate dark and light periods for our study. We selected the test pool based on its community composition which appeared to be reasonably characteristic of many of the ‘deep’ pools in the study (*pers. obs.*). Dissolved oxygen (DO, mg O_2 l^{-1}) and % saturation were measured in the pool immediately when it was uncovered by the falling tide (Orion Star A223 DO with polarographic O_2 electrode, Thermo Scientific, Waltham, MA USA). A dark period was then simulated by covering the pool with an opaque black polythene sheet. DO and % saturation were recorded every five minutes for 30 minutes (dark period), after which time the polythene sheet was removed. DO and %

saturation were then recorded every five minutes for a further 30 minutes (light period) under natural daylight conditions.

Respiratory demand (R) reached a constant rate after 20 minutes in the dark period (Table 1; Figure 1). However, based on the advice of Noël et al. (2010), we considered 30 minutes to be the optimal duration of the dark period in order to allow a higher degree of gas exchange from which to calculate metabolic rate (Table 1). This longer dark period would also minimise the % saturation of the pools in advance of the subsequent light period, thereby reducing the risk of supersaturation. Net primary productivity (NPP) reached a linear phase after 15 minutes in the light period (Table 1; Figure 1), but was supersaturated after 25 minutes, causing a reduction in gas exchange rate. We therefore considered 15-20 minutes to be the optimal light period duration, which would be adjusted on a case-by-case basis depending on the level of gas exchange and % saturation recorded in pools after 15 minutes.

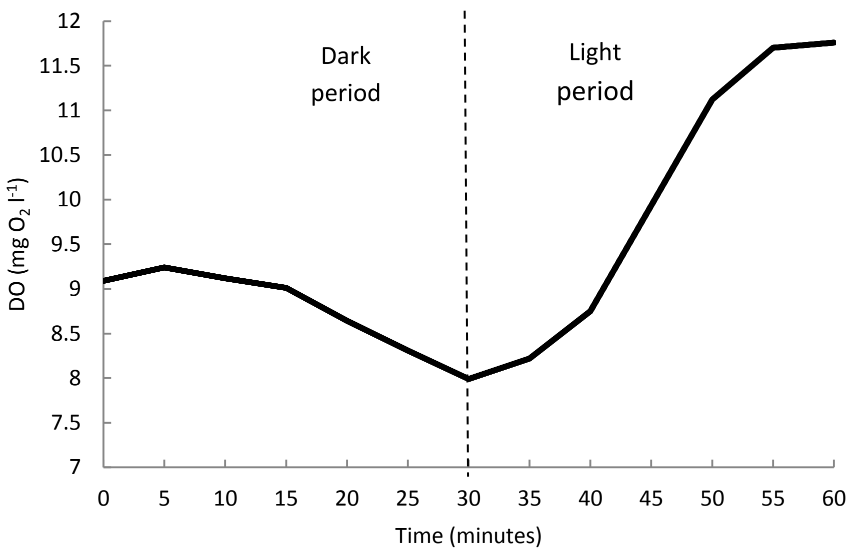

Figure 1 Dissolved oxygen recorded in test rock pool at Aberystwyth at 5-minute intervals during simulated dark and light periods.

Table 1 Dissolved oxygen and % saturation recorded in test rock pool at Aberystwyth at 5-minute intervals during simulated dark and light periods. 'Rate of change per 5-min interval' reflects respiratory demand (R) during the dark period and net primary productivity (NPP) during the light period. Approximate linear phases of gas exchange are highlighted in bold.

Time (minutes)	DO ($mg\ O_2\ l^{-1}$)	Saturation (%)	Change in DO over dark/light period ($mg\ O_2\ l^{-1}$)	Rate of change per 5-min interval ($mg\ O_2\ l^{-1}\ min^{-1}$)
0 (Start of dark period)	9.09	118.4	-	-
5	9.24	121.3	-0.15	-0.030
10	9.12	118.8	-0.03	0.024
15	9.01	116.9	0.08	0.022
20	8.64	110.3	0.45	**0.074**
25	8.31	105.7	0.78	**0.066**
30 / 0 (Start of light period)	7.99	105.7	1.10	**0.064**
5	8.22	105.3	0.23	0.046
10	8.75	112.5	0.76	0.106
15	9.93	126.9	1.94	**0.236**
20	11.12	143.8	3.13	**0.238**
25	11.7	150.0	3.71	0.116
30	11.76	152.2	3.77	0.012

Ambient light levels during rock pool incubations

Field incubations at the end of this study were necessarily carried out on four separate days in October 2014, since pools needed to be sampled within 15 minutes of emersion from the tide at four different locations. We selected the optimal survey period based on the most favourable weather conditions available (i.e. clear sunny days with low wind; Noël et al. 2010) coincident with spring low tides, and monitored photosynthetic active radiation (PAR) at half-hourly intervals throughout the incubations (PAR 'Special' SKP210 1 Channel sensor with SKP200 display meter, Skye Instruments Ltd., Llandrindod Wells, UK). A one-way Kruskal-Wallis test was used to test for differences in mean PAR between incubation surveys. This non-parametric test was used because of heterogeneity of variances and unbalanced replication of PAR readings during the four surveys.

Mean PAR levels were between 900 and 1000 µmol photon m^{-2} s^{-1} during each of the four rock pool incubations (Table 2) and there was no significant difference between the four survey days ($\chi^2(3) = 0.090$, $P = 0.993$). Noël et al. (2010) suggested that PAR >1500 µmol photon m^{-2} s^{-1} is preferable for measuring ecosystem-function by field incubations, since community-scale algal photosaturation requires higher irradiance than commonly-reported thallus-scale saturation (Binzer and Middelboe 2005). It may not, therefore, be possible to make inferences regarding the production potential of the artificial and natural rock pools in this study (i.e. productivity estimations were likely to be less than their maximum potential). However, since ambient conditions were not significantly different across the four survey days, it was reasonable to make relative comparisons of productivity between treatments.

Table 2 Mean (± SE) PAR levels recorded during rock pool incubations at the four study sites on four consecutive days in October 2014.

Incubation	**Mean PAR (± SE) (µmol photon m^{-2} s^{-1})**
Aberystwyth (8/10/14)	908 (± 109.5)
Borth (9/10/14)	978 (± 71.9)
Tywyn (10/10/14)	1000 (± 56.5)
Clarach (11/10/14)	923 (± 165.5)

Appendix V

Water chemistry and physical disturbance in artificial rock pools

Water chemistry and physical disturbance in artificial rock pools

Water chemistry

The maximum, minimum and mean range of water chemistry parameters recorded over the course of the study in 'deep' (12 cm) and 'shallow' (5 cm) artificial pools were compared. The mean range was calculated as the range in values recorded in each pool over 30 months, averaged over nine replicate pools, thus reflecting the degree of fluctuation in water chemistry in 'deep' and 'shallow' habitats. 'Shallow' artificial rock pools experienced slightly wider fluctuations in temperature and pH, but not salinity, compared to 'deep' artificial pools (Table 1).

Table 1 Maximum, minimum and mean range (n = 9) in water chemistry parameters recorded in 'deep' and 'shallow' artificial rock pools over the course of the study. Mean range was calculated as the range in values recorded in each pool over 30 months, averaged over nine replicates, thus reflecting the degree of fluctuation in water chemistry in 'deep' and 'shallow' habitats.

	Temperature (°C)		**Salinity (‰)**		**pH**	
	Deep	**Shallow**	**Deep**	**Shallow**	**Deep**	**Shallow**
Absolute max.	25.9	26.7	40	40	10.22	10.19
Absolute min.	7.8	7.8	30	30	7.97	7.18
Mean range (± SE)	16.8 (± 0.3)	17.3 (± 0.3)	6.8 (± 0.8)	6.8 (± 0.5)	1.5 (± 0.1)	2.1 (± 0.2)

Physical disturbance

The Scheirer-Ray-Hare test (Sokal and Rohlf 1995) was used to compare the volume (V) of total sediment, sand and coarse sediments retained in 'deep' and 'shallow' artificial pools over the course of the study. This non-parametric extension of the Kruskal-Wallis test was used because of heterogeneity of variance in the data, even following transformation. A two-way design was used with fixed factors Depth (two levels: deep, shallow) and Survey Time (12 levels: May 2012, Jun 2012, Jul 2012, Oct 2012, Jan 2013, Apr 2013, Jul 2013, Oct 2013, Jan 2014, Apr 2014, Jul 2014, Oct 2014), and n = 9. Survey Time was treated as a fixed factor because sediment deposition events were considered temporally-independent of one another. Analyses were carried out in R (R Core Team 2012).

'Shallow' artificial rock pools experienced desiccation events more frequently (observed on 13 occasions) than 'deep' artificial pools (observed on 6 occasions). However, 'deep' pools retained more sediments than 'shallow' ones over the course of the study (Scheirer-Ray-Hare $SS/MS_{tot} = 23.129$, $P < 0.001$; Figure 1). In particular, the deeper pools tended to retain more coarse sediments (i.e. gravel and pebbles) than the shallower pools (Scheirer-Ray-Hare $SS/MS_{tot} = 63.447$, $P < 0.001$; Figure 1), whereas there was no significant difference in the volume of sand retained in the two habitats over 30 months (Scheirer-Ray-Hare $SS/MS_{tot} = 1.769$, $P = 0.183$). Nonetheless, 'shallow' pools retained sand more frequently than 'deep' pools (Figure 1).

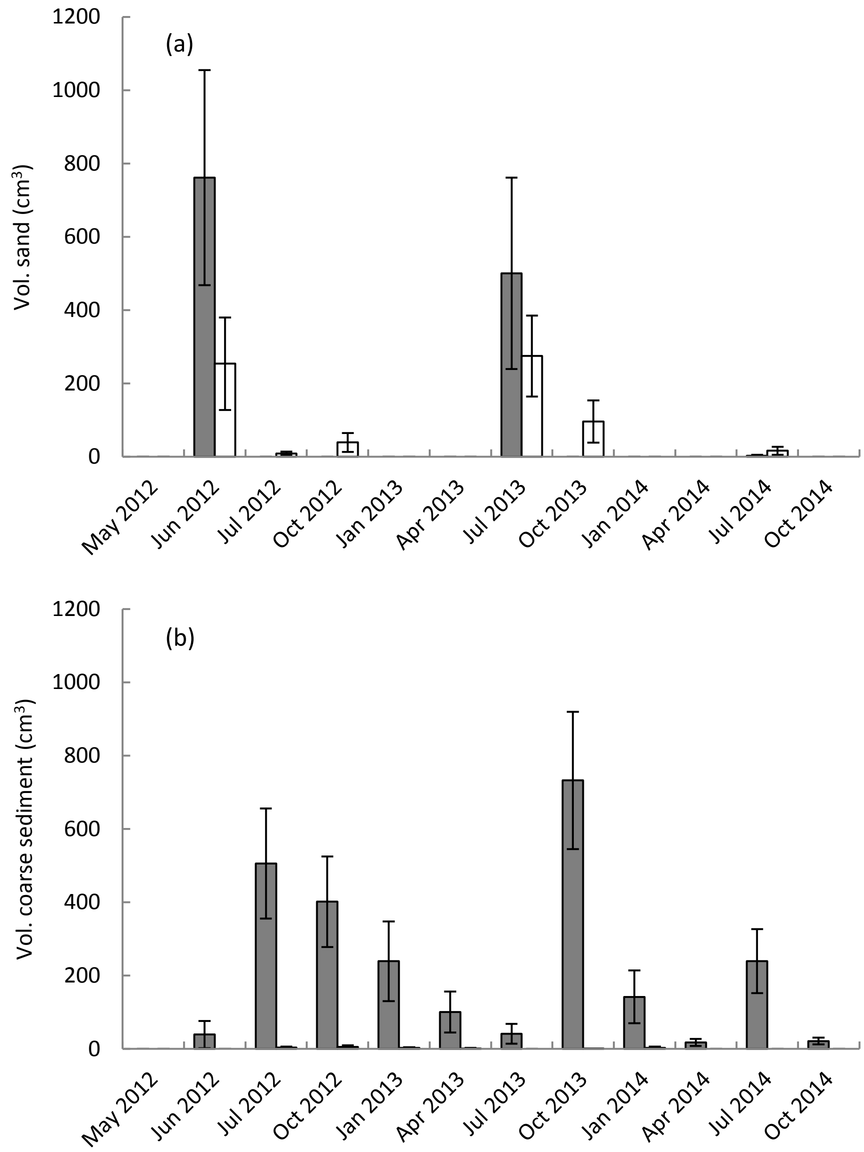

Figure 1 Mean volume (± SE, n = 9) of (a) sand and (b) coarse sediment in 'deep' (grey bars) and 'shallow' (open bars) artificial rock pools over 30 months (April 2012 – October 2014).

Appendix VI

Summary of rock pool replicates used for each analysis

Summary of rock pool replicates used for each analysis

Table 1 Experimental replicates (artificial rock pools, emergent rock surfaces and natural rock pools) installed/initiated throughout the study.

D: 'Deep' replicates, S: 'Shallow' replicates

Site	Spring 2012	Autumn 2012	Spring 2013
Tywyn	Artificial pools: D1-9, S1-9 Emergent rock: D1-9, S1-9	Artificial pools: D1-5, S1-5	Artificial pools: D1-5, S1-5
Aberystwyth	Natural pools: D1-5, S1-5	Natural pools: D1-5, S1-5	Natural pools: D1-5, S1-5
Borth	Natural pools: D1-5, S1-5	Natural pools: D1-5, S1-5	Natural pools: D1-5, S1-5
Clarach	Natural pools: D1-5, S1-5	Natural pools: D1-5, S1-5	Natural pools: D1-5, S1-5

Table 2 Experimental replicates (artificial rock pools, emergent rock surfaces and natural rock pools) included in each analysis.

D: ‘Deep’ replicates, S: ‘Shallow’ replicates; *: replicates pooled over depths

Analysis	n	Spring 2012					Autumn 2012				Spring 2013			
		Tywyn		Aber	Borth	Clarach	Tywyn	Aber	Borth	Clarach	Tywyn	Aber	Borth	Clarach
		Artificial pools	Emergent rock	Natural pools	Natural pools	Natural pools	Artificial pools	Natural pools	Natural pools	Natural pools	Artificial pools	Natural pools	Natural pools	Natural pools
H1: comparing artificial rock pools with emergent rock surfaces														
Total richness & species accumulation	18*	D1-9 S1-9	D1-9 S1-9											
Mean richness	9	D1-9 S1-9	D1-9 S1-9											
H2: comparing deep and shallow artificial rock pools														
Total richness & species accumulation	9	D1-9 S1-9												
Mean richness	9	D1-9 S1-9												
Mean GPP	9	D1-9 S1-9												
Community structure	9	D1-9 S1-9												
H3: comparing artificial rock pools with natural rock pools														
Total richness & species accumulation	10*	D1-5 S1-5		D1-5 S1-5	D1-5 S1-5	D1-5 S1-5								
Mean richness	10*	D1-5 S1-5		D1-5 S1-5	D1-5 S1-5	D1-5 S1-5								
Mean GPP	5	D1-5		D1-5	D1-5	D1-5								
Community structure	5	D1-5 S1-5		D1-5 S1-5	D1-5 S1-5	D1-5 S1-5								

H4: comparing artificial rock pools installed in Spring 2012 and Autumn 2012														
Total richness & species accumulation	10*	D1-5 S1-5					D1-5 S1-5							
Mean richness	10*	D1-5 S1-5					D1-5 S1-5							
Community structure	5	D1-5 S1-5					D1-5 S1-5							
Comparison natural pools (total richness & species accumulation)	10*						D1-5 S1-5	D1-5 S1-5	D1-5 S1-5	D1-5 S1-5				
Comparison natural pools (mean richness)	10*						D1-5 S1-5	D1-5 S1-5	D1-5 S1-5	D1-5 S1-5				
Comparison natural pools (community structure)	5						D1-5 S1-5	D1-5 S1-5	D1-5 S1-5	D1-5 S1-5				
H5: comparing artificial rock pools installed in Spring 2012 and Spring 2013														
Total richness & species accumulation	10*	D1-5 S1-5									D1-5 S1-5			
Mean richness	10*	D1-5 S1-5									D1-5 S1-5			
Community structure	5	D1-5 S1-5									D1-5 S1-5			
Comparison natural pools (total richness & species accumulation)	10*										D1-5 S1-5	D1-5 S1-5	D1-5 S1-5	D1-5 S1-5
Comparison natural pools (mean richness)	10*										D1-5 S1-5	D1-5 S1-5	D1-5 S1-5	D1-5 S1-5
Comparison natural pools (community structure)	5										D1-5 S1-5	D1-5 S1-5	D1-5 S1-5	D1-5 S1-5

Appendix VII

Questionnaire

<u>Questionnaire:</u> The Potential Benefits of Artificial Coastal Defence Structures

Please complete the following questions and contribute your opinions to this study.

1. What is the **primary purpose** of coastal defence structures?
   [Choose 1 option]
   - ☐ Protect the land against flooding and erosion
   - ☐ Stabilise the coastline
   - ☐ Provide hard substrate for marine life to colonise
   - ☐ Provide hard substrate for mariculture of commercial species
   - ☐ Provide suitable refuge for commercial fisheries species
   - ☐ Increase amenity value / access for recreation
   - ☐ Increase landscape value
   - ☐ Other (please specify):

2. What are the **secondary purposes** of coastal defence structures?
   [Choose all that apply]
   - ☐ Protect the land against flooding and erosion
   - ☐ Stabilise the coastline
   - ☐ Provide hard substrate for marine life to colonise
   - ☐ Provide hard substrate for mariculture of commercial species
   - ☐ Provide suitable refuge for commercial fisheries species
   - ☐ Increase amenity value / access for recreation
   - ☐ Increase landscape value
   - ☐ Other / None (please specify):

3. What are the potential **benefits** (not purpose) of coastal defence structures?
   [Choose 5. Rank in order of importance (1=most important, 5 = least important)]
   - ☐ Protect the land against flooding and erosion
   - ☐ Stabilise the coastline
   - ☐ Provide hard substrate for marine life to colonise
   - ☐ Provide hard substrate for mariculture of commercial species
   - ☐ Provide suitable refuge for commercial fisheries species
   - ☐ Increase amenity value / access for recreation
   - ☐ Increase landscape value
   - ☐ Other / None (please specify):

4. What are the potential **negative impacts** of coastal defence structures?
   [Choose 5. Rank in order of importance (1=most important, 5 = least important)]
   - ☐ Spoil the landscape
   - ☐ Degrade the natural environment
   - ☐ Alter natural coastal processes
   - ☐ Expensive
   - ☐ Encourage the spread of non-native species
   - ☐ Encourage colonisation of non-natural assemblages
   - ☐ Dangerous
   - ☐ None – they do not cause any negative impacts
   - ☐ None – their importance for protecting the coast outweighs any negative impact
   - ☐ Other (please specify):

5. What are **most important considerations** when planning coastal defence works (i.e. construction or maintenance of structures)?
   [Choose 5. Rank in order of importance (1=most important, 5 = least important)]

   - ☐ Defence function
   - ☐ Longevity
   - ☐ Cost
   - ☐ Environmental impact
   - ☐ Amenity value
   - ☐ Visual impact
   - ☐ Carbon footprint
   - ☐ Biotic colonisation
   - ☐ Local public support
   - ☐ Impact on tourism
   - ☐ Other (please specify):

6. How **supportive** are you of the construction of additional coastal defence structures around the UK?
   [Please indicate on the scale]

   ○—○—○—○—○—○—○—○—○—○

   Not supportive at all ... Very supportive

7. If they were *multi-functional* structures[1], would your level of support change? How **supportive** are you of the construction of additional *multi-functional* coastal defence structures around the UK?
   [Please indicate on the scale]

   ○—○—○—○—○—○—○—○—○—○

   Not supportive at all ... Very supportive

[1] A coastal defence structure that delivers secondary ecological and/or socio-economic benefits, thus supporting drivers for sustainable development, is considered a *multi-functional* structure (Challinor and Hall, 2008)

8. Thinking about your answers above, **why** would you feel more/less supportive of new coastal defences if they were multi-functional structures?
   [Choose all that apply]

More supportive:

- ☐ Might as well get the most out of new developments
- ☐ This would enhance the environment
- ☐ This would reduce the impact on the environment
- ☐ This is what the government is encouraging us to do
- ☐ This would further scientific knowledge
- ☐ This would increase amenity value
- ☐ This would provide alternative income opportunities
- ☐ This would be good for the economy
- ☐ This would be more likely to get consent
- ☐ Other (please specify):

Less supportive:

- ☐ This is not what they are for – they are there to protect the coast
- ☐ This would be more expensive
- ☐ This would compromise their function
- ☐ This would cause more impact to the environment
- ☐ This would reduce the amenity value in my area
- ☐ This would pose a risk to the public
- ☐ Other (please specify):

Indifferent:

- ☐

9. What type of multi-functional structure would you be **most supportive** of?
[Choose 5. Rank in order of importance (1=most important, 5 = least important)]

- ☐ One that supports species of conservation value
- ☐ One that increases habitat complexity
- ☐ One that supports a natural rocky shore community
- ☐ One that supports commercially valuable species
- ☐ One that attracts more tourists to the area
- ☐ One that improves surfing conditions
- ☐ One that improves recreational fisheries
- ☐ One that provides refuge for commercial fisheries species
- ☐ One that provides a good place to go rockpooling
- ☐ One that can be used for research or education purposes
- ☐ Other (please specify):

~~~~~~~~~~~~~~*THANK YOU FOR YOUR TIME*~~~~~~~~~~~~~~

NAME ____________________

ORGANISATION /
AREA OF INTEREST ____________________

In order to further our understanding of this topic we are conducting a more thorough perception study using the Delphi method[2] in Autumn 2014. This approach will allow identification of differences in perceptions between key representatives of different 'expert' groups. It may also allow tendency towards a consensus, thus informing planning decisions that seek to achieve a balance between ecological and socio-economic considerations.

If you are interested in the findings of this study please indicate and provide your contact details below:

____

[2] The Delphi method provides an interactive communication structure between the researcher and 'experts' in the field. Questions are asked and the information is analysed and fed back via further questions in an iterative process, until some consensus is reached, providing synthesis/clarity on a question.
~~~~~~~~~~~~~~

Appendix VIII

Delphi Survey Letter of Participation

This research forms part of a PhD research study: "Artificial coastal defence structures as surrogate habitats for natural rocky shores: giving nature a helping hand." This work is being undertaken by Ally Evans (Aberystwyth University), in collaboration with Dr Pippa Moore (Aberystwyth University), Dr Louise Firth (NUI Galway), Prof Stephen Hawkins (Southampton University), Marine Ecological Solutions Ltd. and the Knowledge Economy Skills Scholarships (KESS).

MARINE ECOLOGICAL SOLUTIONS kess Ysgoloriaethau Sgiliau Economi Gwybodaeth Knowledge Economy Skills Scholarships IBERS Athrofa y Gwyddorau Biolegol, Amgylcheddol a Gwledig Institute of Biological, Environmental and Rural Sciences

IBERS
Edward Llwyd Building
Aberystwyth University
Penglais Campus
Aberystwyth
SY23 3FG
27th August 2014

Dear Participant,

Thank you for agreeing to take part in this study about the **Potential Secondary Benefits of Artificial Coastal Defence Structures**. We appreciate that you are very busy and will endeavour to minimise the time commitment involved in taking part.

The UK's marine policy statement (sections 2.6.1.3 & 2.6.1.4) advises that new coastal/marine developments should not only avoid harm to marine ecology, but may also provide opportunities for building-in 'beneficial features'. In response, there is growing scientific interest in the development of novel *multi-functional* structures that can provide various secondary benefits, beyond the primary function of coastal protection. The scientific community is calling for clarity on what would be considered and valued as a 'beneficial feature' of coastal defence developments, in order to direct research efforts and resources most effectively. We appreciate your support in trying to address this call, and hope that you will recognise the value of your contribution.

Please read the attached background information about the research and the implications of your participation. If you have any outstanding queries or concerns then please do not hesitate to contact me via the details below.

Yours sincerely,

Ally Evans

PhD Research Candidate
Marine Ecology Research Group of Dr. Pippa Moore

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PRIFYSGOL ABERYSTWYTH UNIVERSITY

This research forms part of a PhD research study: "Artificial coastal defence structures as surrogate habitats for natural rocky shores: giving nature a helping hand." This work is being undertaken by Ally Evans (Aberystwyth University), in collaboration with Dr Pippa Moore (Aberystwyth University), Dr Louise Firth (NUI Galway), Prof Stephen Hawkins (Southampton University), Marine Ecological Solutions Ltd. and the Knowledge Economy Skills Scholarships (KESS).

A] Background to the research

Around 20% of the UK coast is protected by some form of artificial coastal defence infrastructure[1]. Anticipated climate change and increasing coastal development means that more defences are likely to be necessary in the future. The construction of any artificial structure on the shore will inevitably have some negative impact on the existing natural habitat, and in many cases 'soft' engineering approaches (e.g. managed realignment) are preferable to hard engineering. However, Shoreline Management Plans around the UK continue to recommend 'Hold the Line' policies for many coastal areas which require hard coastal defence protection for the foreseeable future.

The UK Marine Policy Statement requires that new marine and coastal developments should not only avoid harm to the environment, but should also provide opportunities for building-in 'beneficial features' for marine ecology. In response, there is growing scientific interest in the development of novel *multi-functional* structures that can provide various secondary 'benefits', beyond the primary function of coastal protection. In order to ensure research efforts and resources are invested effectively, it is first necessary to address the question of ***what constitutes a secondary 'benefit' of artificial coastal defence structures?*** Aside from the primary function (i.e. protection against flooding and coastal erosion), secondary benefits of coastal defence structures may be:

- **Ecological**, e.g. increased productivity as a result of the development of a natural rocky shore assemblage; colonisation of a species/habitat of conservation importance.
- **Social**, e.g. added amenity value from improved surfing conditions, access for recreational sea angling, rockpooling.
- **Economic**, e.g. enhanced tourism from added amenity value; mariculture of shellfish or algae; increased fisheries productivity through functioning as fish aggregation devices.

To determine what secondary benefits would be most valued in coastal defence developments, we are undertaking a perception study using a social science technique called the Delphi method.

B] What is the Delphi method?

The Delphi method provides an interactive communication structure between the researcher and a panel of experts. Qualitative or quantitative questions are asked and the information is analysed and fed back via further questions in an iterative process, until some consensus is reached, providing synthesis / clarity on a question.

This recognised technique draws out expert judgement on highly complex and subjective problems that cannot be easily addressed using conventional survey techniques. This approach will allow identification of differences in perceptions between key representatives of different 'expert' groups. It may also allow tending towards consensus to inform planning decisions that seek to achieve a balance between ecological and socio-economic considerations.

If you would like to know more about the Delphi method, please contact me for some suggested literature.

[1] Marine Climate Change Impacts Partnership (MCCIP). 2013. Annual Report Card. DOI: 10.14465/2013.arc09.071-086

C] <u>What will be asked of you?</u>

1. First, you will be asked to confirm that you give your free and informed consent to take part in this study (please read the Ethical Declaration section below).

2. Next, you will be emailed with a series of 3 questions and asked to respond by email within 3 weeks. You will be asked to respond fully and thoughtfully with your own personal opinions. These opinions should be given in light of your expert professional judgement, *but will not be attributed to the official stance of any organisation/company with which you are associated*.

3. Your responses will be analysed and anonymously[2] incorporated into a synthesis of responses from all panel members. This will be returned to you as part of the second round of questions to determine whether, given the rationale of other respondents, your perceptions are modified.

4. You will be asked to respond to 3 rounds of questioning in total, with 2 - 3 weeks to respond each time (see planned schedule in Appendix I).

5. The final round of questioning will be completed before the end of November 2014.

6. Finally, you will be sent a synthesis of findings from the study and asked to indicate your level of agreement with the statements within.

A more detailed timeline of the study, with estimated time contribution is included in Appendix I.

D] <u>Objectives of this research</u>

The objectives of this research are to:

1. Conduct a Delphi Study to determine participants' perceptions of what constitutes a secondary benefit of artificial coastal defence structures (and their order of priority).

2. Identify differences/agreement between panel members from different sectors.

3. Feedback responses to participants via iterative rounds of questioning.

4. Tend towards consensus to inform balanced planning decisions.

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[2] Panel members' answers will be anonymised but attributed to the sector from which their expertise is derived, e.g. 'Conservation', 'Engineering Consultant', etc. Their answers will not be considered representative of the whole sector, nor of any organisation with which they are associated. No person or organisation will be identified in this study unless express permission is given in advance.

This research forms part of a PhD research study: "Artificial coastal defence structures as surrogate habitats for natural rocky shores: giving nature a helping hand." This work is being undertaken by Ally Evans (Aberystwyth University), in collaboration with Dr Pippa Moore (Aberystwyth University), Dr Louise Firth (NUI Galway), Prof Stephen Hawkins (Southampton University), Marine Ecological Solutions Ltd. and the Knowledge Economy Skills Scholarships (KESS).

E] Ethical declaration

- Data will be collected from a balanced panel[3] of participants with their freely-given informed consent.
- Findings will be reported accurately and truthfully via a PhD thesis of Aberystwyth University and a peer-reviewed publication.
- Participants have the right to withdraw from the study at any time and for any reason.
- Anonymity and privacy of participants will be respected. Identities will be kept confidential and express permission will be sought from individuals before attributing quotes, data, etc. to them in published findings.
- Data will be stored in a secure manner as outlined by Aberystwyth University Guidelines for Research Involving Human Participants.

END

[3] For the Delphi method, balanced participation does not necessarily translate to an equal number of experts from each sector. In this study, the panel will comprise experts from the following sectors (numbers in parentheses indicate number of panel members from the sector): Academic Specialist (1), Academic Non-Specialist (2), Ecological Consultant (2), Engineering Consultant (2), Statutory Bodies – Coastal Management & Nature Conservation (4), Local Authority (2) and Conservation (2).

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Appendix I

Please see below the planned schedule for the Delphi Study. Although we aim to be as flexible as possible, please bear in mind that each round of questions cannot commence until we have received and synthesised all panel members’ responses from the preceding round. Therefore, any delay in returning your answers may result in a delay for the whole study and may cause inconvenience to other panel members. Alternatively, we may have to continue the study without your input. We will endeavour to give you timely reminders about pending response deadlines throughout the study. Please make a note of the “Respond by” dates in red below and let us know as soon as possible if you anticipate any difficulty in meeting any of these deadlines. Many thanks for your cooperation.

Week beginning	**01/09/2014**	**08/09/2014**	**15/09/2014**	**22/09/2014**	**29/09/2014**	**06/10/2014**	**13/10/2014**	**20/10/2014**	**27/10/2014**	**03/11/2014**	**10/11/2014**	**17/11/2014**	**24/11/2014**	**28/11/2014**
Week #	0	1	2	3	4	5	6	7	8	9	10	11	12	**12**
Task	**Read background information. Confirm free & informed consent to take part in the study.**	**Round 1 of questions**			Responses analysed by researchers	**Round 2 of questions**		Responses analysed by researchers.	**Round 3 of questions**		Responses analysed by researchers.	**Final synthesis: Indicate level of agreement**		**END**
Respond by	**08/09/2014**	**26/09/2014**			n/a	**17/10/2014**		n/a	**07/11/2014**		n/a	**28/11/2014**		
Anticipated time required (hours)	1	2			0	2		0	2		0	1		**TOTAL = 8 hours**

Appendix IX

Delphi Survey Questions – Rounds 1, 2 and 3

This research forms part of a PhD research study: “Artificial coastal defence structures as surrogate habitats for natural rocky shores: giving nature a helping hand.” This work is being undertaken by Ally Evans (Aberystwyth University), in collaboration with Dr Pippa Moore (Aberystwyth University), Dr Louise Firth (NUI Galway), Prof Stephen Hawkins (Southampton University), Marine Ecological Solutions Ltd. and the Knowledge Economy Skills Scholarships (KESS).

08/09/2014

DELPHI STUDY ROUND 1: SCOPING ROUND

Dear **Participant**,

Thank you once again for agreeing to take part in this Delphi Study about the **Potential Secondary Benefits of Artificial Coastal Defence Structures**.

Please find below 3 questions which make up Round 1 of the study. Please answer all questions as fully and as thoughtfully as possible; bulleted lists are fine but please provide rationale for your comments throughout. You are reminded once again that your answers won’t be attributed to any organisation/company with which you are associated, and that your answers will be anonymised but reported as having been given by an expert from the sector in which you work.

Please return your answers to me at aje9@aber.ac.uk **by Friday 26th September**. Please let me know if you foresee any difficulty in returning your answers within this time frame, or if you have any further questions.

Yours sincerely,

Ally Evans

PhD Research Candidate
Marine Ecology Research Group of Dr. Pippa Moore

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This research forms part of a PhD research study: "Artificial coastal defence structures as surrogate habitats for natural rocky shores: giving nature a helping hand." This work is being undertaken by Ally Evans (Aberystwyth University), in collaboration with Dr Pippa Moore (Aberystwyth University), Dr Louise Firth (NUI Galway), Prof Stephen Hawkins (Southampton University), Marine Ecological Solutions Ltd. and the Knowledge Economy Skills Scholarships (KESS).

DELPHI STUDY ROUND 1: SCOPING ROUND

With predicted climate change and increasing coastal development, we anticipate that additional hard sea defences will be necessary around the UK, and that existing defences will need to be maintained. The UK Marine Policy Statement advises that marine developments should not only avoid harm to marine ecology, but may also provide opportunities for building-in 'beneficial features'. In response, there is growing scientific interest in the development of novel *multi-functional* structures that can provide various secondary 'benefits', beyond the primary function of coastal protection.

In order to ensure research efforts and resources are invested effectively, it is first necessary to address the question of what constitutes a secondary 'benefit' of artificial coastal defence structures.

Please answer the 3 questions below. You are advised to read all 3 questions before attempting to answer Question 1.

QUESTION 1 (of 3) **What are the most important considerations when planning coastal defence works (i.e. construction or maintenance of engineered coastal defence structures)?** Considerations may be technical, ecological, social, economic, etc. Please answer fully and provide rationale for your comments.
Please write your answer here:

This research forms part of a PhD research study: “Artificial coastal defence structures as surrogate habitats for natural rocky shores: giving nature a helping hand.” This work is being undertaken by Ally Evans (Aberystwyth University), in collaboration with Dr Pippa Moore (Aberystwyth University), Dr Louise Firth (NUI Galway), Prof Stephen Hawkins (Southampton University), Marine Ecological Solutions Ltd. and the Knowledge Economy Skills Scholarships (KESS).

<u>QUESTION 2</u> (of 3) **What are the potential secondary benefits (not purpose) of engineered coastal defence structures (i.e. beyond their primary function of providing protection against flooding and erosion)?** Secondary benefits may be technical, ecological, social, economic, etc. Please answer fully and provide rationale for your comments.
Please write your answer here:

This research forms part of a PhD research study: “Artificial coastal defence structures as surrogate habitats for natural rocky shores: giving nature a helping hand.” This work is being undertaken by Ally Evans (Aberystwyth University), in collaboration with Dr Pippa Moore (Aberystwyth University), Dr Louise Firth (NUI Galway), Prof Stephen Hawkins (Southampton University), Marine Ecological Solutions Ltd. and the Knowledge Economy Skills Scholarships (KESS).

QUESTION 3 (of 3) **Would you be more supportive of the construction of additional coastal defences around the UK if they were multi-functional structures (i.e. ones that deliver secondary ecological and/or socio-economic benefits)? If so, why would you be more supportive? If not, why would you be less supportive / neutral?** Please answer fully and provide rationale for your comments.
Please write your answer here:

END

This research forms part of a PhD research study: "Artificial coastal defence structures as surrogate habitats for natural rocky shores: giving nature a helping hand." This work is being undertaken by Ally Evans (Aberystwyth University), in collaboration with Dr Pippa Moore (Aberystwyth University), Dr Louise Firth (NUI Galway), Prof Stephen Hawkins (Southampton University), Marine Ecological Solutions Ltd. and the Knowledge Economy Skills Scholarships (KESS).

06/10/2014

DELPHI STUDY ROUND 2: CONVERGENCE ROUND

Dear **Participant**,

Thank you for your continued involvement in this Delphi Study about the **Potential Secondary Benefits of Artificial Coastal Defence Structures**.

Below you will find 3 further questions which make up Round 2 of the study. You have received a synthesis of the responses we received from Round 1. ***Please read this information as it may inform your answers in Round 2*****.**

Please be assured that your detailed responses from Round 1 will not be discarded, but will be utilised in our ongoing analyses. The premise of the Delphi technique is to illicit and untangle detailed considerations necessary to address complex questions. However, in order to progress with the study we have condensed the detailed information into broad conceptual elements that you will be asked to rank in priority order. Please answer all questions as thoughtfully as possible and provide rationale for your ranking throughout.

You are reminded once again that your answers won't be attributed to any organisation/company with which you are associated, and that your answers will be anonymised but reported as having been given by an expert from the sector in which you work.

Please return your answers to me at aje9@aber.ac.uk **by Friday 17th October**. Please let me know if you foresee any difficulty in returning your answers within this time frame, or if you have any further questions.

Yours sincerely,

Ally Evans
PhD Research Candidate
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This research forms part of a PhD research study: "Artificial coastal defence structures as surrogate habitats for natural rocky shores: giving nature a helping hand." This work is being undertaken by Ally Evans (Aberystwyth University), in collaboration with Dr Pippa Moore (Aberystwyth University), Dr Louise Firth (NUI Galway), Prof Stephen Hawkins (Southampton University), Marine Ecological Solutions Ltd. and the Knowledge Economy Skills Scholarships (KESS).

DELPHI STUDY ROUND 2: CONVERGENCE ROUND

With predicted climate change and increasing coastal development, we anticipate that additional hard sea defences will be necessary around the UK, and that existing defences will need to be maintained. The UK Marine Policy Statement advises that marine developments should not only avoid harm to marine ecology, but may also provide opportunities for building-in 'beneficial features'. In response, there is growing scientific interest in the development of novel *multi-functional* structures that can provide various secondary 'benefits', beyond the primary function of coastal protection.

In order to ensure research efforts and resources are invested effectively, it is first necessary to address the question of what constitutes a secondary 'benefit' of artificial coastal defence structures.

PLEASE NOTE:

We acknowledge all of the points made in Round 1 regarding the need for further discussion about whether/how to defend, the need for considerations to be made on a case-by-case basis, and the necessity that any built-in secondary benefits do not compromise more crucial considerations (such as being "fit for purpose"). However, in order to fulfil the study objectives, please base your answers on the hypothetical scenario that *new hard defences have been deemed an appropriate solution for defence*, and please allow some generalisation in your responses to allow us to understand conceptual priorities.

We appreciate that it is often difficult to rank considerations on a priority scale (e.g. some things are inherently linked, some things are mandatory not choice, etc.), but please stick to a linear ordered ranking (each number used only once). We encourage you to qualify any caveats and/or discomforts about your ranking in the boxes below.

Please answer the 3 questions below. You are advised to read all 3 questions before attempting to answer Question 1.

This research forms part of a PhD research study: "Artificial coastal defence structures as surrogate habitats for natural rocky shores: giving nature a helping hand." This work is being undertaken by Ally Evans (Aberystwyth University), in collaboration with Dr Pippa Moore (Aberystwyth University), Dr Louise Firth (NUI Galway), Prof Stephen Hawkins (Southampton University), Marine Ecological Solutions Ltd. and the Knowledge Economy Skills Scholarships (KESS).

QUESTION 1 (of 3)

What are the most important considerations when planning coastal defence works (i.e. construction or maintenance of engineered coastal defence structures)?

The following considerations are derived from the themes/subthemes that emerged from Round 1 responses (see synthesis report, Table 1). Please rank in order of priority on a scale of 1-20 (1 = high; 20 = low). Please indicate your ranking in the boxes below.

CONSIDERATION	RANK (1-20)
Justification (i.e. considered necessary, supported by SMP and Coastal Strategy)	
Fit for purpose (i.e. provides adequate, appropriate and efficient protection over the required timeframe)	
In line with environmental legislation and planning guidelines	
Part of a sustainable strategy	
Cost and funding	
Unintentional alteration to coastal processes (i.e. changes to sediment and flow dynamics not intended as part of the defence function)	
Opportunities for research and development (e.g. new engineering solutions, experimental units for investigating marine/coastal ecology)	
Positive socio-economic impacts on local communities and businesses (e.g. through enhanced amenity, recreation, fisheries, navigation, tourism, employment, etc.)	
Negative socio-economic impacts on local communities and businesses (e.g. through reduced amenity, recreation, fisheries, navigation, tourism, employment, etc.)	
Opportunities for education and outreach	
Impact on landscape	
Culture and heritage	
Public safety (i.e. during construction and operation, rather than as a result of the defence function)	
Community support	
Carbon footprint	
Positive ecological impacts as a result of defence function (i.e. protect/extend existing sedimentary and hinterland habitats and species)	
Positive ecological impacts as a result of novel habitat (e.g. enhanced connectivity/resilience of rocky habitats, habitat for exploited species, habitat for species of conservation concern, habitat heterogeneity, etc.)	
Negative ecological impacts during construction and operation (e.g. loss/disturbance of habitats/species, facilitate spread of invasive non-native species, etc.)	
Negative ecological impacts as a result of extraction and transport of raw materials	
Multi-functionality (i.e. provides secondary ecological and/or socio-economic benefits)	

Question 1 continued…

…Question 1 continued

Please provide rationale for your rankings. You may refer to information you have already provided in Round 1 (or copy and paste text again here in context). Include in your rationale:

- Reasons for ranking in the order you have (particularly at the top and bottom ends of the scale)
- Your level of confidence in the ranks you have given (i.e. did you find it easy to rank each above/below another or are there some that caused you particular trouble?)
- Additional considerations that should be included in the list.
- Redundant/unimportant considerations that should be removed from the list.

Please write your rationale here:

This research forms part of a PhD research study: "Artificial coastal defence structures as surrogate habitats for natural rocky shores: giving nature a helping hand." This work is being undertaken by Ally Evans (Aberystwyth University), in collaboration with Dr Pippa Moore (Aberystwyth University), Dr Louise Firth (NUI Galway), Prof Stephen Hawkins (Southampton University), Marine Ecological Solutions Ltd. and the Knowledge Economy Skills Scholarships (KESS).

QUESTION 2 (of 3)

What are the potential secondary benefits that can be gained from multi-functional coastal defence structures (i.e. beyond their primary function of providing protection against flooding and erosion)?

The following potential secondary benefits are derived from the themes/subthemes that emerged from Round 1 responses (see synthesis report, Table 2). Please rank in order of priority on a scale of 1-20 (1 = high; 20 = low). Please indicate your ranking in the boxes below.

POTENTIAL SECONDARY BENEFITS	RANK (1-20)
Improve funding potential	
Foster community support	
Fulfil requirements of environmental legislation and planning guidelines	
Avoid costs of clean-up operations (i.e. following flood events/storm damage)	
Opportunities for research and development – new engineering solutions	
Opportunities for research and development – investigating marine/coastal ecology	
Positive feedback in stability of structure (i.e. reduce maintenance requirements)	
Reduced carbon footprint / carbon sequestration	
House other technologies (e.g. turbines, masts, etc.)	
Positive socio-economic impacts on local communities and businesses (e.g. through enhanced amenity, recreation, fisheries, navigation, tourism, employment, etc.)	
Wider economy (e.g. through increased land use potential, wider employment, etc.)	
Opportunities for education and outreach	
Enhanced/safeguarded landscape	
Enhanced/safeguarded culture and heritage	
Enhanced/safeguarded public safety (i.e. in terms of interaction with the structure, rather than as a result of the defence function)	
Positive ecological impacts as a result of defence function (i.e. protect/extend existing sedimentary and hinterland habitats and species)	
Positive ecological impacts as a result of novel habitat (e.g. enhanced connectivity/resilience of rocky habitats, habitat for exploited species, habitat for species of conservation concern, habitat heterogeneity, etc.)	
Divert pressure from natural systems (i.e. by providing access for recreation, navigation, fisheries, research, etc.)	
Compensatory habitat creation	
Enhanced biosecurity (i.e. discourage spread of invasive non-native species)	

Question 2 continued…

…Question 2 continued

Please provide rationale for your rankings. You may refer to information you have already provided in Round 1 (or copy and paste text again here in context). Include in your rationale:

- Reasons for ranking in the order you have (particularly at the top and bottom ends of the scale)
- Your level of confidence in the ranks you have given (i.e. did you find it easy to rank each above/below another or are there some that caused you particular trouble?)
- Additional considerations that should be included in the list.
- Redundant/unimportant considerations that should be removed from the list.

Please write your rationale here:

This research forms part of a PhD research study: "Artificial coastal defence structures as surrogate habitats for natural rocky shores: giving nature a helping hand." This work is being undertaken by Ally Evans (Aberystwyth University), in collaboration with Dr Pippa Moore (Aberystwyth University), Dr Louise Firth (NUI Galway), Prof Stephen Hawkins (Southampton University), Marine Ecological Solutions Ltd. and the Knowledge Economy Skills Scholarships (KESS).

QUESTION 3 (of 3)

This question investigates whether (and why) you would be more supportive of the construction of additional coastal defences if they were multi-functional structures. We would also like to gather information about the current barriers to implementation and suggestions for moving forward.

All panel members provided some positive comment in favour of multi-functional structures in Round 1. However, the level of support varied. The following statements have been constructed to reflect the range of opinions expressed (see synthesis report, Section 3), along with other possible opinions created for the purpose of the study. Please indicate which statement you agree with most (choose only 1):

1. I do not support the construction of new hard coastal defences. Multi-functionality would not make me more supportive because overall negative impacts would outweigh any potential secondary benefits.

2. I do not support the construction of new hard coastal defences, but if new defences are deemed necessary then I would be supportive of them being multi-functional.

3. I would be more supportive of the construction of new coastal defences if they were multi-functional.

4. I am supportive of the construction of new multi-functional coastal defences, as long as the built-in secondary benefits do not compromise the primary function or cause additional negative impacts.

5. I am supportive of the construction of new multi-functional coastal defences, as long as evidence can be provided (in advance) that they will provide significant ecological and/or socio-economic benefits.

6. I am supportive of the construction of new hard coastal defences. Multi-functionality would not make me more supportive because I am only concerned that they perform their primary function.

Please provide rationale for your selection. You may refer to information you have already provided in Round 1 (or copy and paste text again here in context). Include in your rationale:

- Reasons for selecting the statement you chose
- Any comment about the other statements (particularly about additional ones you strongly agree with and ones you strongly disagree with)

Please write your rationale here:

Question 3 continued…

…Question 3 continued

In Round 1, several panel members offered information about current barriers to effective implementation of multi-functional coastal defence structures, and also provided suggestions for moving forward (see synthesis report, Table 3). Although we didn't initially request this information, we think it is extremely valuable and would like to gather opinions on these 2 subjects in a more complete manner.

Please rank in order of priority on a scale of 1-7(10) (1 = high; 7(10) = low). Please also add any additional barriers and/or suggestions for moving forward with multi-functional structures.

CURRENT BARRIERS TO EFFECTIVE IMPLEMENTATION	RANK (1-7)
Awareness of / engagement with the concept of multi-functionality	
Developments driven by cost and funding priorities	
Ability to justify additional costs	
Reliable assessment of value	
Lack of evidence that benefits will be realised	
Lack of legislative support	
Lack of policy drive	
Please add any additional barriers:	
SUGGESTIONS FOR MOVING FORWARD	**RANK (1-10)**
Improve awareness and engagement amongst relevant sectors	
Develop new technologies to improve potential of multi-functional structures	
Conduct experimental trials to gather additional evidence	
Conduct cost-benefit analyses of potential secondary benefits	
Make additional resources available to cover cost of multi-functional features	
Expand beneficiary pays principal to include secondary benefits	
Make multi-functionality mandatory for new coastal defences	
Consider multi-functional designs in the planning stage of new defences	
Strengthen legislative framework	
We should not move forward with multi-functional structures as this may lead to sacrificing sustainable coastal management for short-term gains	
Please add any additional suggestions:	

END

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Athrofa y Gwyddorau Biolegol, Amgylcheddol a Gwledig
Institute of Biological, Environmental and Rural Sciences

31/10/2014

DELPHI STUDY ROUND 3: CONVERGENCE ROUND

Dear **Participant**,

Thank you again for your continued involvement in this Delphi Study about the **Potential Secondary Benefits of Artificial Coastal Defence Structures**.

Below you will find 3 further questions which make up Round 3 of the study. You have received a synthesis of the responses we received from Round 2. ***Please read this information as it may inform your answers in Round 3*****.**

Please be assured that your detailed responses from Rounds 1 & 2 will not be discarded, but will be utilised in our ongoing analyses. The premise of the Delphi technique is to illicit and untangle detailed considerations necessary to address complex questions. However, in order to progress with the study we are continuing with condensed lists of broad conceptual elements that you will be asked to rank in priority order. Please answer all questions as thoughtfully as possible. You are not required to provide rationale for your ranking in this round but we will be happy to incorporate any additional comments regarding any aspect of the study.

You are reminded once again that your answers won't be attributed to any organisation/company with which you are associated, and that your answers will be anonymised but reported as having been given by an expert from the sector in which you work.

Please return your answers to me at aje9@aber.ac.uk **by Friday 14th November**. Please let me know if you foresee any difficulty in returning your answers within this time frame, or if you have any further questions.

Yours sincerely,

Ally Evans
PhD Research Candidate
Marine Ecology Research Group of Dr. Pippa Moore

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This research forms part of a PhD research study: "Artificial coastal defence structures as surrogate habitats for natural rocky shores: giving nature a helping hand." This work is being undertaken by Ally Evans (Aberystwyth University), in collaboration with Dr Pippa Moore (Aberystwyth University), Dr Louise Firth (NUI Galway), Prof Stephen Hawkins (Southampton University), Marine Ecological Solutions Ltd. and the Knowledge Economy Skills Scholarships (KESS).

DELPHI STUDY ROUND 3: CONVERGENCE ROUND

With predicted climate change and increasing coastal development, we anticipate that additional hard sea defences will be necessary around the UK, and that existing defences will need to be maintained. The UK Marine Policy Statement advises that marine developments should not only avoid harm to marine ecology, but may also provide opportunities for building-in 'beneficial features'. In response, there is growing scientific interest in the development of novel *multi-functional* structures that can provide various secondary 'benefits', beyond the primary function of coastal protection.

In order to ensure research efforts and resources are invested effectively, it is first necessary to address the question of what constitutes a secondary 'benefit' of artificial coastal defence structures, and further, what secondary benefits would be most desirable.

PLEASE NOTE:

We acknowledge all of the points made in Rounds 1 & 2 regarding the need for further discussion about whether/how to defend, the need for considerations to be made on a case-by-case basis, and the necessity that any built-in secondary benefits do not compromise more crucial considerations (such as being "fit for purpose"). However, in order to fulfil the study objectives, please base your answers on the hypothetical scenario that *new hard defences have been deemed an appropriate solution for defence*, and please allow some generalisation in your responses to allow us to understand conceptual priorities. In particular, when answering Question 2, please refer to the section "Defining the context of potential secondary benefits for Round 3" in the accompanying synthesis report.

We appreciate that it is often difficult to rank considerations on a priority scale (e.g. some things are inherently linked, some things are mandatory not choice, etc.), but please stick to a linear ordered ranking (each number used only once). We have tried to incorporate many of the suggestions from Round 2 to make the ranking process more meaningful in Round 3. We encourage you to qualify any caveats and/or discomforts about your ranking in the boxes below.

Please answer the 3 questions below. You are advised to read all 3 questions before attempting to answer Question 1.

This research forms part of a PhD research study: "Artificial coastal defence structures as surrogate habitats for natural rocky shores: giving nature a helping hand." This work is being undertaken by Ally Evans (Aberystwyth University), in collaboration with Dr Pippa Moore (Aberystwyth University), Dr Louise Firth (NUI Galway), Prof Stephen Hawkins (Southampton University), Marine Ecological Solutions Ltd. and the Knowledge Economy Skills Scholarships (KESS).

<u>QUESTION 1</u> (of 3)

What are the most important considerations when planning coastal defence works (i.e. construction or maintenance of engineered coastal defence structures)?

Below is a list of considerations compiled from Round 1 & 2 responses (see Round 2 synthesis report, Table 1 & discussion).

In the 1st column "RANK 1", please rank in order of priority based on what you think <u>the current order of priority</u> is in practice. In the 2nd column "RANK 2", please rank in order of priority based on what you think <u>the order of priority should be</u>. Rank on a scale of 1-10 (1 = high; 10 = low). If you don't feel qualified to complete "RANK 1", please indicate and complete "RANK 2" only.

1) CONSIDERATIONS	RANK 1 (1-10)	RANK 2 (1-10)
Essential criteria (i.e. part of a sustainable strategy, justification, in line with environmental legislation and planning guidelines, public safety, fit-for-purpose, no unintentional alteration to coastal processes, affordable/funding available)		
Net ecological impacts (i.e. assuming minimum requirements are met and not including risk reduction from primary defence function: e.g. loss/disturbance of habitats/species, dispersal of invasive non-native species, extraction of raw materials, novel habitat/refuge for exploited species or species of conservation interest, etc.)		
Net socio-economic impacts on local communities and businesses (i.e. assuming minimum requirements are met and not including risk reduction from primary defence function: e.g. reduced/enhanced amenity, recreation, fisheries, navigation, tourism, employment, etc.)		
Cost (i.e. assuming funding is available)		
Net landscape impacts (i.e. assuming minimum requirements are met)		
Level of community support (i.e. assuming minimum requirements are met)		
Opportunities for research and development (e.g. new engineering designs, experimental units to investigate marine/coastal ecology)		
Carbon footprint (i.e. assuming minimum requirements are met: e.g. processing and transport of raw materials, construction emissions, etc.)		
Net culture and heritage impacts (i.e. assuming minimum requirements are met and not including risk reduction from primary defence function: e.g. loss/damage of heritage features or archaeology, platform for art installations, etc.)		
Opportunities for education and outreach (e.g. platform for environmental education, etc.)		

…Question 1 continued

In compiling this reduced list of considerations we have forfeited some detail regarding the relative importance of associated positive and negative impacts on ecology and local communities/businesses. Please indicate your level of agreement with the following statement:

"Considerations for avoiding/minimising negative impacts are more important than considerations for creating/maximising positive impacts."

Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
☐	☐	☐	☐	☐

Please provide any additional comments regarding Q1. For example:

- Reasons for ranking in the order you have.
- Your level of confidence in the ranks you have given (i.e. did you find it easy to rank each above/below another or are there some that caused you particular trouble?).
- The information presented in the Round 2 Synthesis Report (Table 1, Figure 1 or Q1 discussion).
- The statement above and your level of agreement with it.

Please write your comments here (optional):

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QUESTION 2 (of 3)

What are the potential secondary benefits that can be gained from multi-functional coastal defence structures (i.e. beyond their primary function of providing protection against flooding and erosion)?

PLEASE ENSURE YOU HAVE READ THE SECTION “DEFINING THE CONTEXT OF POTENTIAL SECONDARY BENEFITS FOR ROUND 3” IN THE ROUND 2 SYNTHESIS REPORT BEFORE ANSWERING THIS QUESTION.

Below is a list of potential secondary benefits that can be gained from multi-functional coastal defence structures, compiled from Round 1 & 2 responses (see Round 2 synthesis report, Table 2 & discussion). Please rank in order of priority on a scale of 1-15 (1 = high; 15 = low).

2a) POTENTIAL SECONDARY BENEFIT DESIGN FEATURES	RANK (1-15)
Refuge for exploited species (e.g. build-in refuge habitat suitable for exploited species to allow populations to persist)	
Habitat heterogeneity in structure design (e.g. build-in mosaic of habitats such as rocky substrate, sediments, saltmarsh patches, etc.)	
Habitat for natural rocky shore communities (e.g. build-in microhabitat complexity and use materials suitable for natural rocky shore communities to colonise)	
Habitat for species of conservation interest (e.g. build-in habitat suitable for wintering birds, BAP species, etc.)	
Safeguarded biosecurity (e.g. build-in features to remove/reduce competitive advantage of non-native invasive species)	
Enhanced amenity/recreation (e.g. build-in surf reef design, promenade, beach access, recreational fishing platform, etc.)	
Enhanced commercial fisheries (e.g. build-in refuge/nursery habitat for commercial species)	
Mariculture opportunities (e.g. build-in facilities for mussel/macroalgae culture)	
Opportunities for research and development – new engineering solutions (e.g. trial novel materials and structural designs)	
Opportunities for research and development – investigating marine/coastal ecology (e.g. build-in experimental mesocosm units)	
Reduced carbon footprint (e.g. use novel low-carbon materials or recycled waste materials)	
House other technologies (e.g. build-in turbines, masts, etc.)	
Enhanced landscape value (e.g. use natural materials, subtle design or aesthetically-attractive design)	
Enhanced culture and heritage value (e.g. build-in art installations)	
Opportunities for education and outreach (e.g. build-in facilities for public engagement or environmental education)	

…Question 2 continued

Below is a list of potential reasons for building-in secondary benefits to hard coastal defence structures, compiled from Round 1 & 2 responses (see Round 2 synthesis report, Table 2 & discussion). Please rank in order of priority on a scale of 1-10 (1 = high; 10 = low).

2b) REASONS FOR BUILDING-IN SECONDARY BENEFITS	RANK (1-10)
Increase likelihood of scheme progression (i.e. by fostering public support and improving partnership funding potential)	
Divert pressure from natural systems (i.e. by providing access for recreation, fisheries, research, co-location with other technologies etc.)	
Positive ecological impacts (i.e. through enhanced connectivity/resilience of rocky habitats, habitat for exploited species, habitat for species of conservation concern, habitat heterogeneity, etc.)	
Positive socio-economic impacts on local communities and businesses (i.e. through enhanced amenity, recreation, fisheries, navigation, tourism, employment, etc.)	
Enhance/safeguard landscape (i.e. by using natural materials, subtle design or aesthetically-attractive design)	
Culture and heritage (i.e. by building-in art installations, etc.)	
Research and development (i.e. gather evidence necessary for moving forward with multi-functional coastal defences by trialling novel engineering designs and improving knowledge of marine/coastal ecology)	
Reduce maintenance requirements (i.e. by building-in positive feedback in stability of structure)	
Reduce carbon footprint (i.e. by using low carbon technology, recycled materials, etc.)	
Education and outreach (i.e. by building-in facilities for public engagement and environmental education)	

Please provide any additional comments regarding Q2. For example:

- Reasons for ranking in the order you have.
- Your level of confidence in the ranks you have given (i.e. did you find it easy to rank each above/below another or are there some that caused you particular trouble?).
- The information presented in the Round 2 Synthesis Report (Table 2, Figure 2 or Q2 discussion).

Please write your comments here (optional):

QUESTION 3 (of 3)

This question investigates whether (and why) you would be more supportive of the construction of additional coastal defences if they were multi-functional structures. We would also like to gather information about the current barriers to implementation and suggestions for moving forward.

Below is a statement constructed to reflect the general caveated level of support for multi-functional coastal defence structures expressed in Round 1 & 2 (see Round 2 synthesis report, Figure 3 and discussion). Assuming that hard coastal defence structures have been deemed the appropriate option for a particular shoreline, please indicate your level of agreement with the following statement:

“Where hard coastal defence structures are deemed necessary, I would be more supportive of them being multi-functional structures, as long as:

- built-in secondary benefits do not compromise primary defence function or cause additional negative impacts, and
- evidence can be provided that intended ecological and/or socio-economic benefits will be realised.”

Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
☐	☐	☐	☐	☐

Please provide any additional comments regarding this question (optional):

…Question 3 continued

Below is a list of current barriers to effective implementation and suggestions for moving forward with multi-functional coastal defence structures, compiled from Round 1 & 2 responses (see Round 2 synthesis report, Table 3 & discussion). Please rank in order of priority on a scale of 1-10 (1 = high; 10 = low).

CURRENT BARRIERS TO EFFECTIVE IMPLEMENTATION	RANK (1-10)
Developments driven by cost and funding priorities	
Ability to justify additional costs	
Lack of policy drive and legislative support	
Reliable assessment of value	
Lack of evidence that benefits will be realised	
Awareness of / engagement with the concept of multi-functionality	
Poor communication between sectors during planning	
Lack of collaboration with EU/international partners (i.e. knowledge exchange)	
Lack of understanding of ecology of manmade habitats	
Lack of well-understood "products" (i.e. ecological engineering solutions)	
SUGGESTIONS FOR MOVING FORWARD	**RANK (1-10)**
Consider multi-functional designs in the planning stage of new defences	
Strengthen legislative framework	
Conduct cost-benefit analyses of potential secondary benefits	
Conduct experimental trials to gather additional evidence	
Improve awareness and engagement amongst relevant sectors	
Develop new technologies to improve potential of multi-functional structures	
Make additional resources available to cover cost of multi-functional features	
Expand beneficiary pays principal to include secondary benefits	
Collaborate with EU/international partners (knowledge exchange)	
Develop "products" that can be incorporated into scheme designs	

Please provide any additional comments regarding Q3. For example:

- Reasons for ranking in the order you have.
- Your level of confidence in the ranks you have given (i.e. did you find it easy to rank each above/below another or are there some that caused you particular trouble?).
- The information presented in the Round 2 Synthesis Report (Table 3, Figure 3 or Q3 discussion).

Please write your comments here (optional):

END

Appendix X

Delphi Survey Synthesis reports – Rounds 1, 2 and 3

This research forms part of a PhD research study: "Artificial coastal defence structures as surrogate habitats for natural rocky shores: giving nature a helping hand." This work is being undertaken by Ally Evans (Aberystwyth University), in collaboration with Dr Pippa Moore (Aberystwyth University), Dr Louise Firth (NUI Galway), Prof Stephen Hawkins (Southampton University), Marine Ecological Solutions Ltd. and the Knowledge Economy Skills Scholarships (KESS).

Athrofa y Gwyddorau Biolegol, Amgylcheddol a Gwledig
Institute of Biological, Environmental and Rural Sciences

DELPHI STUDY ROUND 1 SYNTHESIS

OVERVIEW

With predicted climate change and increasing coastal development, we anticipate that additional hard sea defences will be necessary around the UK, and that existing defences will need to be maintained. The UK Marine Policy Statement advises that marine developments should not only avoid harm to marine ecology, but may also provide opportunities for building-in 'beneficial features'. In response, there is growing scientific interest in the development of novel *multi-functional* structures that can provide various secondary 'benefits', beyond the primary function of coastal protection.

In Round 1, we asked a panel of 16 experts from 7 different sectors[1] to answer 3 open-ended questions. We were interested in similarities and differences in opinions between panel members from different sectors. Figure 1 illustrates a cluster analysis of responses given by panel members. The clustering is based on the number of references to each of the themes and subthemes outlined in this report. In Round 1, there was apparent similarity in responses provided by Academics (Specialist and Non-specialist), Conservationists and Ecological Consultants, and also Local Authorities and Engineering Consultants. Statutory Body responses were most similar to those provided by Academics. Although this may be of interest to the study as we move forward, we reiterate that responses provided by panel members are not considered representative of the sector to which they are assigned.

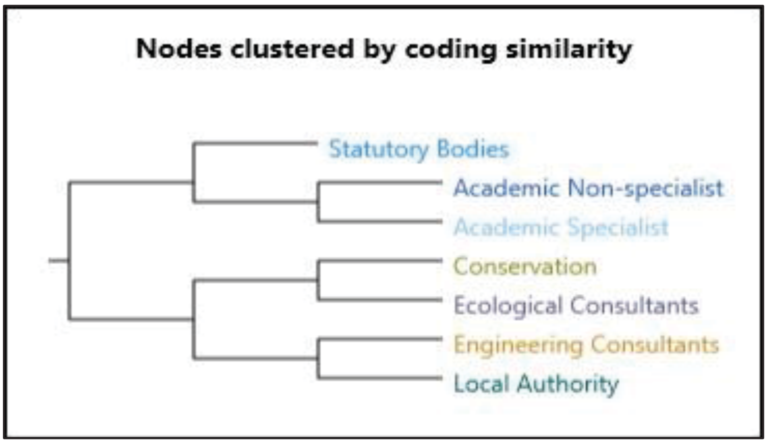

Figure 1 Cluster analysis of Round 1 responses. Responses were coded by themes and subthemes and clustering was undertaken based on Jaccard's similarity coefficient for the number of references coded to each theme

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[1] The panel comprised experts from the following sectors (numbers in parentheses indicate number of panel members from the sector): Academic Specialist (1), Academic Non-Specialist (2), Ecological Consultant (2), Engineering Consultant (2), Statutory Bodies – Coastal Management & Nature Conservation (5), Local Authority (2) and Conservation (2).

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QUESTION 1

What are the most important considerations when planning coastal defence works (i.e. construction or maintenance of engineered coastal defence structures)?

From Q1 responses, 11 overarching "Main Themes" emerged, which we further organised into 50 "Subthemes" (Table 1).

The most talked-about themes were:

Technical Considerations:
(Referenced 123 times by 16 panel members)

This theme included discussion about the physical engineering design (e.g. material, shape, footprint, etc.) of coastal defences and the need to take a case-by-case approach to ensure schemes are "fit-for-purpose" (i.e. they provide adequate, appropriate and efficient protection over the required timeframe, with consideration of future projections). There was also comment about the need to consider timing of works, and to plan ahead for all stages of the development, including pre-construction, construction, operation, maintenance and decommissioning.

Ecological Considerations:
(Referenced 106 times by 15 panel members)

This theme included discussion about the need to consider the potential positive and negative ecological impacts of coastal defence developments. Potential positive impacts discussed were protecting existing hinterland habitats, ecological enhancements, and the introduction of novel habitats. Potential negative impacts discussed were disturbance/loss of habitats and species, pollution, extraction/transport of raw materials, and again the introduction of novel habitats. There was equal reference to localised impacts and wider ecosystem-scale impacts.

Economic Considerations:
(Referenced 90 times by 16 panel members)

This theme included discussion about the potential positive and negative economic impacts of coastal defence developments. Potential positive impacts related to increased asset value, commercial fisheries, and enhanced tourism, recreation and amenity value from increased land-use potential. Potential negative impacts related to all of these same subthemes, and additionally to conflicts with other sea users (e.g. navigation), and the biosecurity risk of invasive non-native species colonising structures. The majority of discourse referred to local communities and businesses, with infrequent mention of wider employment and economies. There was frequent reference to the importance of cost considerations (including cost-benefit analyses) and funding sources. The Defra policy statement[2] which sets out the partnership approach to funding flood and coastal erosion risk management in England was referred to. The policy encourages developers to attract funding contributions from multiple parties, and it was suggested that this gives rise to the "beneficiary-pays principal".

Social Considerations:
(Referenced 78 times by 15 panel members)

This theme included discussion about the potential positive and negative social impacts of coastal defence developments. There was a lot of overlap between social and economic considerations, since many of the subthemes are pertinent to both overarching main themes. In addition to those issues mentioned above (in Economic Considerations: commercial fisheries, tourism, recreation and amenity), there was reference to potential

[2] https://www.gov.uk/government/publications/flood-and-coastal-resilience-partnership-funding

positive and negative implications for public safety, culture and heritage, landscape, and education and outreach (positive only). There was also comment on the importance of community support for a scheme. Again, most discussion referred to the impacts on local communities and businesses.

Policy Considerations:
(Referenced 23 times by 9 panel members)

This theme included discussion about the importance of Shoreline Management Plans and Coastal Strategies for determining whether/how a stretch of coast should be defended. These comments frequently referred to local, national and European planning guidelines and environmental legislations. There was also comment about the need to carry out formal environmental assessments for any developments. Some commented on the importance of gaining community support via public consultation.

Coastal Processes:
(Referenced 13 times by 11 panel members)

This theme included discussion about the importance of considering the implications of coastal defence developments on local and wider coastal processes (i.e. geomorphology, sediment dynamics, tide/current regimes). Comment was made regarding the importance of effectively altering processes as intended to provide flood and erosion protection, and also the importance of understanding/mitigating the implications of unintentional alterations further along the coast.

Other:
(Referenced <5 times by <5 panel members)

The remaining themes (Sustainability, Collaboration, Complexity, Justification, and Research and Development) were each referenced infrequently. We do not consider this to be an automatic reflection of lack of importance as considerations, but may simply be less frequently discussed.

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Table 1 List of Main Themes and Subthemes that emerged from panel responses to Q1

Main Theme	Subtheme
Coastal Processes	Coastal Processes
Collaboration	Collaboration
Complexity	Complex
Justification	Justification
Research & Development	Reasearch & Development
Sustainability	Sustainability
Economic Considerations	Asset Value
	Biosecurity
	Commercial Fisheries
	Cost
	Economic General
	Funding
	Local Community & Businesses
	Navigation
	Recreation & Amenity
	Tourism
Social Considerations	Commercial Fisheries
	Community Support
	Culture & Heritage
	Education & Outreach
	Landscape
	Local Community & Businesses
	Public Safety
	Recreation & Amenity
	Social General
	Tourism
Policy Considerations	Community Support
	Environmental Assessment
	Environmental Legislation
	Planning Guidelines
	SMP & Coastal Strategy
Technical Considerations	All Stages of Development
	Carbon Footprint
	Fit For Purpose
	Monitoring
	Multi-Purpose
	Physical Design
	Technical General
	Timing of Works
Ecological Considerations	Disturbance/Loss of Habitats & Species
	Ecological Enhancement
	Ecological General
	Ecosystem Scale
	Environmental Sustainability
	Introduction of Artificial Habitat
	Local Environment
	Mitigation
	Pollution
	Protect Existing Habitats
	Raw Materials

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QUESTION 2

What are the potential secondary benefits (not purpose) of engineered coastal defence structures (i.e. beyond their primary function of providing protection against flooding and erosion?

From Q2 responses, we identified 6 overarching "Main Themes", which we organised into 43 "Subthemes" (Table 2).

Several panel members stressed that consideration of potential secondary benefits would need to be taken on a case-by-case basis, and that there may be associated *dis-benefits* in some cases. Acknowledging this, the most talked-about themes were:

Potential Economic Secondary Benefits:
(Referenced 123 times by 16 panel members)

This theme included discussion about potential economic secondary benefits through enhanced tourism, recreation and amenity, commercial fisheries and navigation. Increased asset value and land use potential was also mentioned. The majority of the discussion was with reference to local communities and businesses, with infrequent comment about wider employment and economies. There was reference to safeguarding biosecurity by discouraging the spread of invasive non-native species, and suggestion that effective defence schemes would lead to reduced clean-up costs. Positive feedback incorporated into the design (i.e. sediment accretion) would stabilise structures, reducing future maintenance costs. Finally, it was suggested that built-in secondary benefits could improve the funding potential for new developments.

Potential Social Secondary Benefits:
(Referenced 139 times by 14 panel members)

There was a lot of overlap in discussion about potential economic and social secondary benefits. As above (in Potential Economic Secondary Benefits), there was discussion about enhanced tourism, recreation and amenity, commercial fisheries, and asset value, again mostly in relation to local communities and businesses. There was also comment about enhanced/safeguarded landscape value, culture and heritage, and public safety. There was reference to provision of education and outreach opportunities, and suggestion that built-in secondary benefits could foster community support for new developments.

Potential Ecological Secondary Benefits:
(Referenced 63 times by 16 panel members)

This theme included discussion about potential ecological secondary benefits in the form of protecting and extending existing habitat, creation of new rocky habitat for native reef species, birds, species of conservation concern, and exploited species, creation of compensatory habitat, increased habitat heterogeneity (large- and small-scale), and enhancing connectivity and resilience of habitats at larger geographic scales. There was reference to biodiversity enhancement in general terms and safeguarding against the spread of invasive non-native species. Finally, there was a suggestion that built-in secondary benefits (such as access and recreational use) could divert pressure from natural habitats.

Other:
(Referenced ≤5 times by ≤5 panel members)

The remaining themes (Potential Policy, Technical, and Research and Development Secondary Benefits) were each referenced infrequently. We do not consider this to be an automatic reflection of lack of importance as considerations, but may simply be less frequently discussed.

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Table 2 List of Main Themes and Subthemes that emerged from panel responses to Q2

Main Theme	Subtheme
Policy	Attract Government Investment
	Foster Community Support
	Improve Funding Potential
	Satisfy Environmental Legislation
	Satisfy Planning Guidelines
Research & Development	Experimental Units
	New Engineering Solutions
Technical	Carbon Sequestration
	House Alternative Energy Technology
	House Other Technology
Ecological	Aggregate Fish
	Avoid Spread of INNS
	Biodiversity Enhancement
	Compensatory Habitat Creation
	Connectivity & Resilience
	Divert Pressure from Natural Systems
	Habitat for Birds
	Habitat for Exploited Species
	Habitat for Native Reef Species
	Habitat for Species of Conservation Concern
	Habitat Heterogeneity
	Protect & Extend Existing Habitat

Main Theme	Subtheme
Economic	Avoid Cost of Clean Up
	Avoid Spread of INNS
	Enhance Commercial Fisheries
	Enhance Recreation & Amenity
	Enhance Tourism
	Improve Funding Potential
	Increase Asset Value
	Local Community & Businesses
	Navigation
	Positive Feedback Stability
	Wider Employment
Social	Community Support
	Education & Outreach Opportunities
	Enhance Commercial Fisheries
	Enhance Culture & Heritage
	Enhance Landscape
	Enhance Recreation & Amenity
	Enhance Tourism
	Increase Asset Value
	Local Community & Businesses
	Public Safety

QUESTION 3

Would you be more supportive of the construction of additional coastal defences around the UK if they were multi-functional structures (i.e. ones that deliver secondary ecological and/or socio-economic benefits)? If so, why would you be more supportive? If not, why would you be less supportive / neutral?

All 16 panel members provided some positive comment in favour of multi-functional structures. However, the level of support varied:

- 1 panel member stated that they were not supportive of new hard defence schemes but that there is a legal requirement to create compensatory habitat when schemes are implemented.

- Several panel members stated that they were not supportive of new hard defence schemes but conceded that *if they were deemed necessary*, then they would be supportive of them being multi-functional.

- Several panel members reiterated that considerations would have to be made on a case-by-case basis and that multi-functionality must not compromise more important considerations (such as being “fit-for-purpose”).

- Several panel members expressed uncaveated support for multi-functional structures.

We untangled the reasons that panel members gave for being *more supportive*, *not more supportive*, and *cautious*, along with themes of discussion about current barriers to effective implementation and suggestions for moving forward (Table 3). It should be noted that panel members were not specifically asked to comment on barriers to effective implementation or suggestions for moving forward. Therefore, it is likely that the information presented is not an exhaustive list of considerations. However, we felt that it was worthy of inclusion and may inspire further discussion in Round 2.

Reasons for being more supportive of multi-functional structures:
(Referenced 58 times by 16 panel members)

Most frequently cited reasons were in relation to the general concept of multi-functional structures (e.g. they are “logical” and “good sense”), and the value of incorporating biodiversity and socio-economic enhancements that can counter negative impacts of developments. There were also several comments about the added cost being justifiable and insignificant in relation to overall scheme costs.

Reasons for not being more supportive of multi-functional structures:
(Referenced 4 times by 3 panel members)

The reasons given for not being supportive of multi-functional structures were that the potential benefits do not mitigate the overall impacts of developments, the approach could sacrifice sustainable management for short-term gains, and that there may be better solutions in future (when referring to “future-proofing” developments).

Reasons for being cautious about multi-functional structures:
(Referenced 34 times by 10 panel members)

Several panel members expressed caution in relation to the need for considerations to be made on a case-by-case basis, the need for more evidence of the potential for realising secondary benefits (and associated *dis-benefits*) and assessing their value, and also about higher priority concerns when planning coastal defence schemes.

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Barriers to effective implementation:
(Referenced 20 times by 8 panel members)

There were suggestions that funding, cost, and awareness within the relevant sectors may be barriers to effective implementation of multi-functional structures at present. Further, a lack of evidence, policy drive and legislative support may also be hindering factors.

Suggestions for moving forward:
(Referenced 38 times by 15 panel members)

Suggestions for moving forward included developing a stronger legislative framework to support sustainable and integrative strategies for coastal defence schemes. There is a need for better engagement from all parties involved, and this needs to happen in the early stages of planning. Several panel members called for further evidence-gathering through trials and cost-benefit analyses. Some suggested that new coastal defences are inevitable and that multi-functionality should be mandatory for new developments (and that resources should be made available for this), whilst others warned that there still needs to be considered debate over whether and how to defend in the first place. Finally, it was suggested that the "beneficiary pays principal" could be extended to secondary benefits via the Partnership Funding scheme in England.

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Table 3 List of reasons given for being more supportive, not more supportive or cautious about multi-functional coastal defence structures, along with current barriers to effective implementation and suggestions for moving forward

Main Theme	Subtheme
More Supportive	Aesthetically Pleasing
	Benefit Species of Conservation Concern
	Best Practice in Other Systems
	Cost Justified/Favourable
	Counter Negative Impacts
	Foster Community Support
	Logical
	Mandatory
	Means of Funding Ecological Improvements
	Multi-functional Concept
	Part of a Sustainable Strategy
	Positive Knock-on Effects
	Technology Exists
	Value of Biodiversity Enhancement
	Value of Socio-Economic Enhancement
Not More Supportive	Future Solutions May be Better
	Impacts Outweigh Secondary Benefits
	Sacrifice Sustainable Management for Short-Term Gains
Cautious	Added Complication
	Associated Dis-benefits
	Case-by-Case Basis
	Conflict with MPAs
	Cost-effective?
	Different Primary Concerns
	Future Solutions May be Better
	Justified if Only Provide Habitat for Common Species?
	More Evidence Needed
	Not a Replacement for Lost Habitat
	Shouldn't be Included Automatically
	Soft Engineering Preferable

Main Theme	Subtheme
Barriers	Assessment of Value
	Awareness and Engagement
	Driven by Cost
	Funding
	Justification of Additional Cost
	Lack of Evidence
	Legislative Support
	Policy Drive
Moving Forward	Additional Resources Made Available
	Assessment of Value
	Beneficiary Pays Principle
	Better Engagement
	Create Incentives
	Defend or Not
	Ecosystem Approach
	Further Investigation
	Increased Defence Inevitable
	Integrative Coastal Planning
	Mandatory
	Partnership Funding
	Planning Stage
	Strengthen Legislative Framework
	Sustainable Strategy
	Technological Advancement

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DELPHI STUDY ROUND 2 SYNTHESIS

OVERVIEW

With predicted climate change and increasing coastal development, we anticipate that additional hard sea defences will be necessary around the UK, and that existing defences will need to be maintained. The UK Marine Policy Statement advises that marine developments should not only avoid harm to marine ecology, but may also provide opportunities for building-in 'beneficial features'. In response, there is growing scientific interest in the development of novel *multi-functional* structures that can provide various secondary 'benefits', beyond the primary function of coastal protection.

In Round 1, we asked a panel of 16 experts from 7 different sectors[3] to answer 3 open-ended questions about multi-functional coastal defence structures. In Round 2, we compiled summary lists from the responses received and asked the panel to rank them on a priority scale.

In this synthesis report we present the overall order of ranks assigned to each of the considerations and also any consensus/conflicts in opinions across different panel members and sectors. We appreciate that the information presented may not reflect the opinions of all panel members, and we acknowledge all comments received regarding the difficulty of such a task and the potential to draw misleading conclusions. Any findings reported from this study will be accompanied with qualifying explanation of the generalisations incorporated into the technique.

We received some valuable comments regarding the level of confidence in assigned ranks and some useful evaluation of the synthesis of responses from Round 1. We have used this feedback to further develop the study and progress into Round 3.

[3] The panel comprised experts from the following sectors (numbers in parentheses indicate number of panel members from the sector): Academic Specialist (1), Academic Non-Specialist (2), Ecological Consultant (2), Engineering Consultant (2), Statutory Bodies – Coastal Management & Nature Conservation (5), Local Authority (2) and Conservation (2).

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QUESTION 1

What are the most important considerations when planning coastal defence works (i.e. construction or maintenance of engineered coastal defence structures)?

From Round 1 responses, we compiled a list of 20 considerations that were cited as important when planning coastal defence works. In Round 2 we asked the panel to rank these in order of priority and provide rationale for their decisions.

Order of priority:

The individual ranks assigned by panel members were converted to scores[4] which were summed over responses from the whole panel. Total scores were then converted back into overall priority rankings between 1 and 20 (1 = high, 20 = low) (Table 1).

The panel ranked "Justification", "Fit for purpose", "Unintentional alterations to coastal processes", "Part of a sustainable strategy" and "In line with environmental legislation and planning guidelines" as the highest priority considerations when planning coastal defence works. At the other end of the scale, the panel ranked "Opportunities for education and outreach", "Culture and heritage", "Carbon footprint", "Opportunities for research and development", and "Community support" as the lowest priority considerations.

In general, considerations for avoiding/minimising negative impacts were ranked higher than considerations for creating/maximising positive impacts. However, several panel members stressed that each of the considerations were of importance, even if ranked low on the scale.

Consensus and conflicts in responses:

To investigate the level of consensus amongst the panel, we plotted box and whisker plots showing the median scores, the variation in ranks assigned by different panel members (i.e. interquartile range[5] and max/min scores), and any outlying ranks assigned to each of the 20 considerations (i.e. ranks lying outside 1.5 times the interquartile range) (Figure 1).

There appears to be a greater degree of consensus in the upper rankings (i.e. smaller interquartile range and shorter whiskers), with the exception of "Cost and funding", which has a very large interquartile range. From comments received we think that this is partly because of ambiguity in the terminology; "Funding" availability would be considered essential to progress with a coastal defence scheme, whereas "Cost" may be a negotiable element considered a higher/lower priority than the numerous other elements of the scheme (see section below regarding "Essential/fundamental/higher-level considerations"). Other conflicted considerations (e.g. "Public safety" and "Multi-functionality", which both have long whiskers) were problematic because they were broadly thought of as "higher-level" considerations which couldn't easily be compared with more specific considerations on a linear rank scale (again, see sections below).

[4] Scores were calculated by subtracting ranks from 21, i.e. inverting ranks 1-20 into more intuitive scores 20-1 (20 = high, 1 = low)
[5] The interquartile range is calculated as the difference between the 3rd quartile (top edge of boxplot, i.e. middle number between the median and the highest value) and the 1st quartile (bottom edge of the boxplot, i.e. middle number between the median and the lowest value), i.e. the interquartile range contains the middle 50% of the values in the data set.

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Table 1 Considerations for planning coastal defence works in order of priority, as indicated by combined rankings of the panel (1 = high, 20 = low).

CONSIDERATION	RANK (1-20)
Justification (i.e. considered necessary, supported by SMP and Coastal Strategy)	1
Fit for purpose (i.e. provides adequate, appropriate and efficient protection over the required timeframe)	2
Unintentional alteration to coastal processes (i.e. changes to sediment and flow dynamics not intended as part of the defence function)	3
Part of a sustainable strategy	4
In line with environmental legislation and planning guidelines	5
Negative ecological impacts during construction and operation (e.g. loss/disturbance of habitats/species, facilitate spread of invasive non-native species, etc.)	6
Cost and funding	7
Negative ecological impacts as a result of extraction and transport of raw materials	8
Impact on landscape	9
Positive ecological impacts as a result of defence function (i.e. protect/extend existing sedimentary and hinterland habitats and species)	10
Negative socio-economic impacts on local communities and businesses (e.g. through reduced amenity, recreation, fisheries, navigation, tourism, employment, etc.)	11
Multi-functionality (i.e. provides secondary ecological and/or socio-economic benefits)	12
Positive ecological impacts as a result of novel habitat (e.g. enhanced connectivity/resilience of rocky habitats, habitat for exploited species, habitat for species of conservation concern, habitat heterogeneity, etc.)	13
Positive socio-economic impacts on local communities and businesses (e.g. through enhanced amenity, recreation, fisheries, navigation, tourism, employment, etc.)	14
Public safety (i.e. during construction and operation, rather than as a result of the defence function)	15
Community support	16
Opportunities for research and development (e.g. new engineering solutions, experimental units for investigating marine/coastal ecology)	17
Carbon footprint	18
Culture and heritage	19
Opportunities for education and outreach	20

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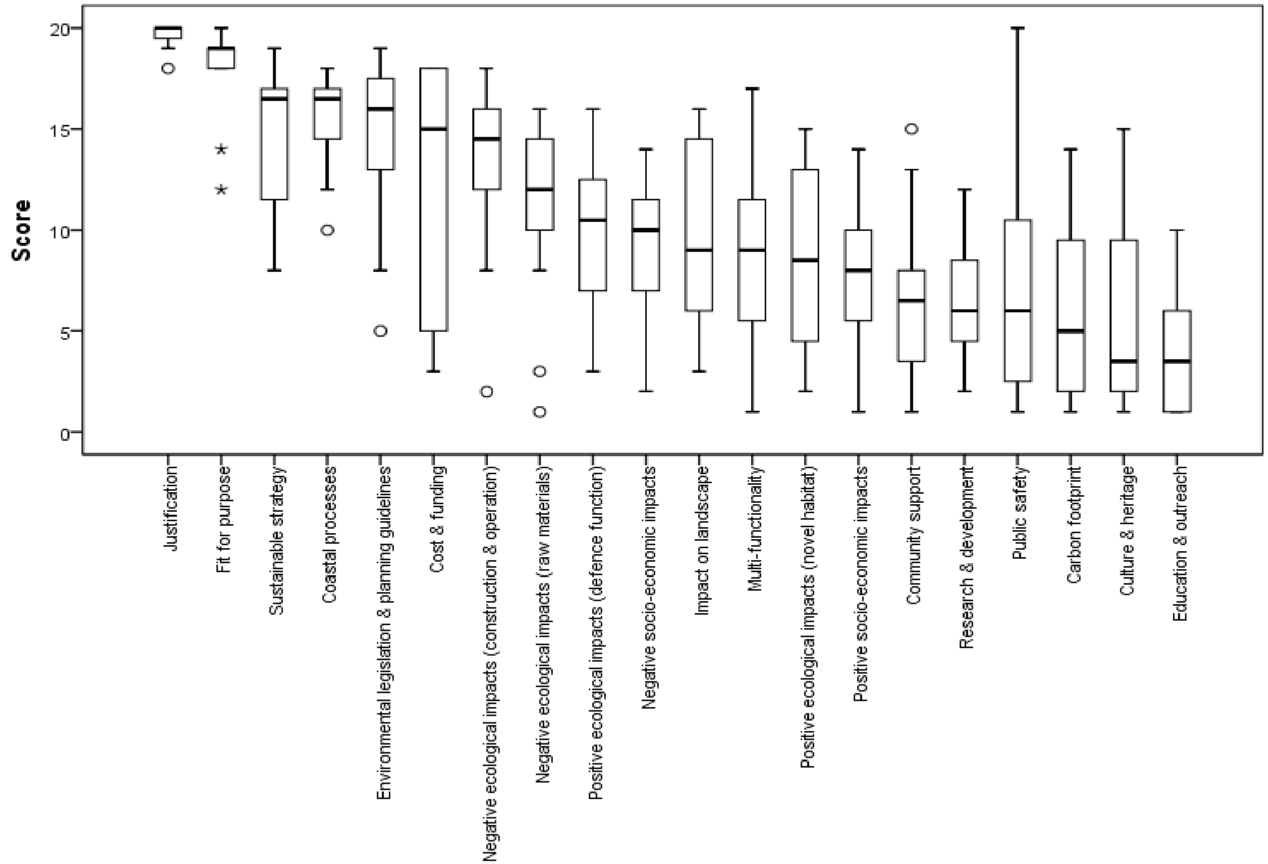

Figure 1 Round 2 Q1 scores assigned by the panel. Box and whisker plots indicate median scores (mid line), interquartile range (box), max/min ranks (whiskers), outliers (circles) and extreme outliers (stars). Scores were calculated by subtracting ranks from 21, i.e. inverting ranks 1-20 into more intuitive scores 20-1 (20 = high, 1 = low).

Confidence in the linear rank scale:

Several panel members commented on the difficulty of ranking a list of 20 considerations on one linear scale of priority. This was anticipated and we suggested that particular focus be given to those ranked at the top and bottom ends of the scale. We envisaged then progressing by dividing the considerations into "Most Important", "Least Important" and "Somewhere in the Middle", expecting that considerations falling into the latter category would have received less attention and/or conviction during the ranking process. (The intention being that these considerations would then be a focus of Round 3.)

However, in light of comments received, it appears more probable/appropriate that the considerations were perceived as "Essential", "Most Important (Non-Essential)" and "Less Important (Non-Essential)". As a consequence, we suspect that the ranks in the middle of the scale were given equal attention to those at the top and bottom ends of the scale. In general, however, there was a lower level of confidence about the middle rankings because the moderate scores assigned did not always reflect their perceived level of importance. For example, "Negative socio-economic impacts" was ranked 11th overall (median score = 10) but several panel members indicated that they felt this was a very important consideration that had been shifted down their priority list because of numerous "essential considerations" that were necessarily ranked higher.

Essential/fundamental/higher-level considerations:

Several panel members commented that "essential" considerations could not reasonably be ranked higher/lower priority than one another. In addition, considerations thought of as "higher-level" were difficult to rank alongside more detailed "implementation-level" considerations. Critically, not all considerations deemed "essential" or "higher-level" were ranked high by all panel members; some were ranked at the bottom of the scale because they were "fundamental" (i.e. taken for granted and/or not up-for-debate).

The top 5 ranked considerations (Table 1) were all referred to as "essential" or "fundamental" by several panel members in their supporting rationale. But some of the middling and lower ranks such as "Multi-functionality", "Public safety" and "Carbon footprint" were *also* referred to as "fundamental" or "higher-level" considerations. In response to comments received we have compiled an amended list of considerations, more tailored to "implementation-level" decision-making, to be taken forward to Round 3 (see comments below).

Amended list of considerations (Round 3 Q1):

Based on comments received from the panel, we have combined "essential" considerations and removed or modified "higher-level" considerations. We hope that this will allow more meaningful ranking in Round 3. Please bear in mind that there may be some ambiguity regarding whether a consideration is definitively "essential" (the panel will be invited to comment on this in Round 3).

We also combined associated positive and negative elements into *net* ecological/socio-economic/etc. impacts. This was done on the basis of apparent consensus that avoiding/minimising negative impacts is more important than creating/maximising positive impacts.

We didn't include elements such as landscape and education/outreach in the "Net socio-economic impacts" consideration because of inherent value beyond their importance to local communities and businesses.

QUESTION 2

What are the potential secondary benefits that can be gained from multi-functional coastal defence structures (i.e. beyond their primary function of providing protection against flooding and erosion?)

From Round 1 responses, we compiled a list of 20 potential secondary benefits that could be gained from multi-functional coastal defence structures. In Round 2 we asked the panel to rank these in order of priority and provide rationale for their decisions.

Order of priority:

The individual ranks assigned by panel members were again converted to scores[6] which were summed over responses from the whole panel. Total scores were then converted back into overall priority rankings between 1 and 20 (1 = high, 20 = low) (Table 2).

The panel ranked "Positive ecological impacts as a result of defence function", "Positive ecological impacts as a result of novel habitat", "Positive socio-economic impacts on local communities and businesses", "Compensatory habitat creation" and "Divert pressure from natural systems" as the highest priority secondary benefits that could be gained from multi-functional coastal defence structures. At the other end of the scale, the panel ranked "Enhanced/safeguarded public safety", "Enhanced/safeguarded culture and heritage", "Reduced carbon footprint / carbon sequestration", "Opportunities for education and outreach", and "Enhanced biosecurity" as the lowest priority secondary benefits.

In general, ecological secondary benefits and localised socio-economic secondary benefits were ranked higher priority than the wider social, economic and technical secondary benefits.

Consensus and conflicts in responses:

To investigate the level of consensus amongst the panel, we again plotted box and whisker plots showing the median scores, the variation in ranks assigned by different panel members (i.e. interquartile range[7] and max/min scores), and any outlying ranks assigned to each of the 20 secondary benefits (i.e. ranks lying outside 1.5 times the interquartile range) (Figure 2).

There appears to be little consensus in the ranks assigned to most of the potential secondary benefits (i.e. large interquartile ranges and/or long whiskers). Exceptions include some of the higher ranked benefits (e.g. "Potential ecological impacts as a result of defence function", "Compensatory habitat creation" and "Positive socio-economic impacts on local communities and businesses") and the lowest ranked benefit ("Enhanced/safeguarded public safety"), which all have lower interquartile ranges and/or shorter whiskers.

From comments received we think that there are several reasons for this lack of consensus, including ambiguity in the question and differences in interpretation. We have tried to untangle all of the valuable feedback received from the panel to develop a more useful list of potential secondary benefits to take forward to Round 3 (see comments below).

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[6] Scores were calculated by subtracting ranks from 21, i.e. inverting ranks 1-20 into more intuitive scores 20-1 (20 = high, 1 = low)
[7] The interquartile range is calculated as the difference between the 3rd quartile (top edge of boxplot, i.e. middle number between the median and the highest value) and the 1st quartile (bottom edge of the boxplot, i.e. middle number between the median and the lowest value). Thus, the interquartile range contains the middle 50% of the values in the data set.

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Table 2 Potential secondary benefits that can be gained from multi-functional coastal defence structures in order of priority, as indicated by combined rankings of the panel (1 = high, 20 = low)

POTENTIAL SECONDARY BENEFITS	RANK (1-20)
Positive ecological impacts as a result of defence function (i.e. protect/extend existing sedimentary and hinterland habitats and species)	1
Positive ecological impacts as a result of novel habitat (e.g. enhanced connectivity/resilience of rocky habitats, habitat for exploited species, habitat for species of conservation concern, habitat heterogeneity, etc.)	2
Positive socio-economic impacts on local communities and businesses (e.g. through enhanced amenity, recreation, fisheries, navigation, tourism, employment, etc.)	3
Compensatory habitat creation	4
Divert pressure from natural systems (i.e. by providing access for recreation, navigation, fisheries, research, etc.)	5
Positive feedback in stability of structure (i.e. reduce maintenance requirements)	6
Wider economy (e.g. through increased land use potential, wider employment, etc.)	7
Enhanced/safeguarded landscape	8
Fulfil requirements of environmental legislation and planning guidelines	9
Opportunities for research and development – new engineering solutions	10
Opportunities for research and development – investigating marine/coastal ecology	11
Avoid costs of clean-up operations (i.e. following flood events/storm damage)	12
House other technologies (e.g. turbines, masts, etc.)	13
Foster community support	14
Improve funding potential	15
Enhanced biosecurity (i.e. discourage spread of invasive non-native species)	16
Opportunities for education and outreach	17
Reduced carbon footprint / carbon sequestration	18
Enhanced/safeguarded culture and heritage	19
Enhanced/safeguarded public safety (i.e. in terms of interaction with the structure, rather than as a result of the defence function)	20

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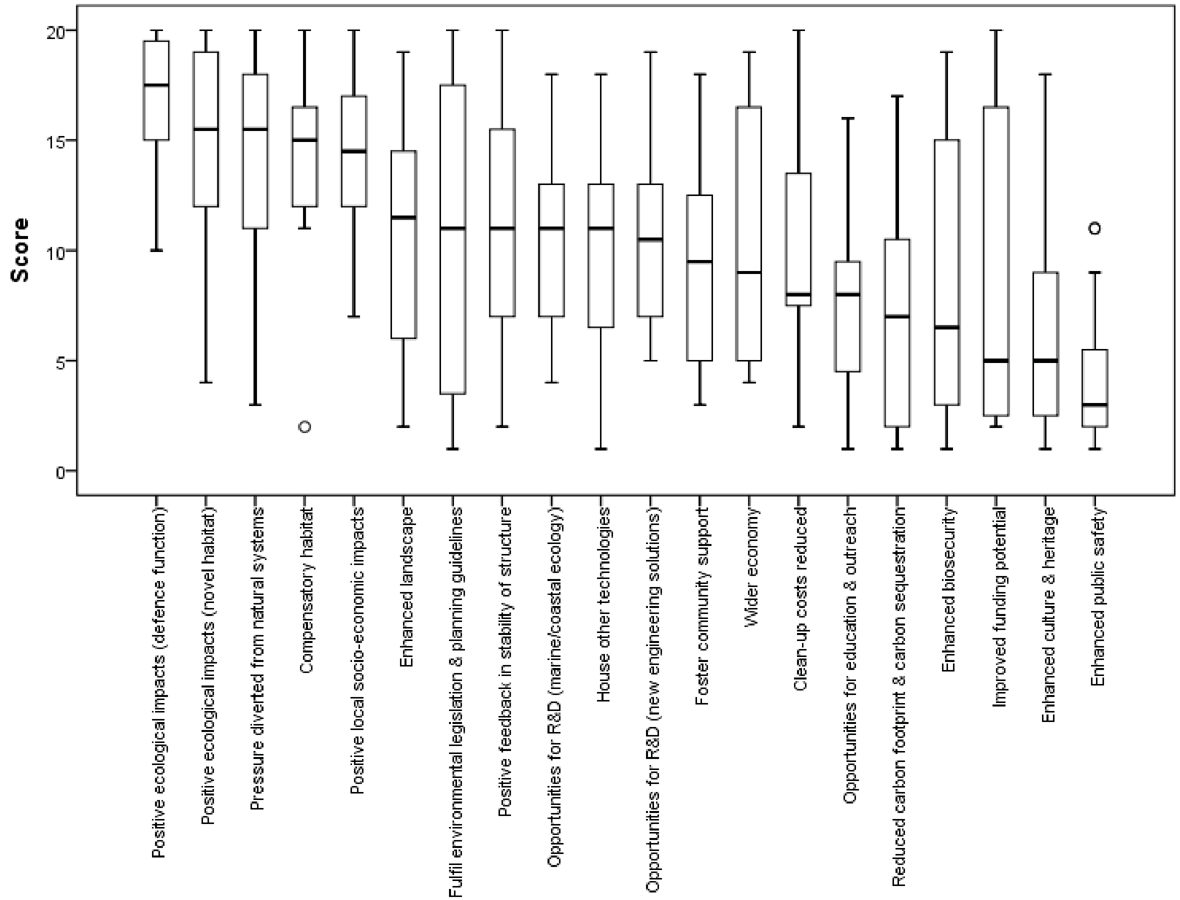

Figure 2 Round 2 Q2 scores assigned by the panel. Box and whisker plots indicate median scores (mid line), interquartile range (box), max/min ranks (whiskers) and outliers (circles). Scores were calculated by subtracting ranks from 21, i.e. inverting ranks 1-20 into more intuitive scores 20-1 (20 = high, 1 = low).

Confidence in the linear rank scale:

Several panel members again commented on the difficulty of ranking a list of 20 potential secondary benefits on one linear scale of priority. This was anticipated and we suggested that particular focus be given to those ranked at the top and bottom ends of the scale. We envisaged then progressing by dividing the benefits into "Most Beneficial", "Least Beneficial" and "Somewhere in the Middle", expecting that considerations falling into the latter category would have received less attention and/or conviction during the ranking process. (The intention being that these considerations would then be a focus of Round 3.)

However, in light of comments received, it appears more probable/appropriate that the potential secondary benefits were perceived as "Potential Secondary Benefits", "Not Secondary Benefits (Higher-level Considerations)", "Not Secondary Benefits (Essential)" and "Not Secondary Benefits (Primary Benefits)". These are discussed further below.

Contested potential secondary benefits:

Panel members commented that the following should not be considered potential secondary benefits because they are "higher-level" considerations:

- "Improve funding potential"
- "Foster community support"
- "Reduced carbon footprint / carbon sequestration"
- "Wider economy"

Panel members commented that the following should not be considered potential secondary benefits because they are "essential":

- "Compensatory habitat creation"
- "Fulfil requirements of environmental legislation and planning guidelines"
- "Positive feedback in stability of structure"
- "Enhance/safeguarded public safety"

Panel members commented that the following should not be considered potential secondary benefits because they are "primary benefits":

- "Avoid costs of clean-up operations"
- "Positive ecological impacts as a result of defence function"

As in Q1, these "higher-level considerations", "essential considerations" and "primary benefits" could not reasonably be ranked alongside more detailed "implementation-level" potential secondary benefits. Critically, these contested considerations were not consistently ranked high or low by all panel members; some were ranked at the top of the scale because of their high importance, while others were ranked at the bottom of the scale because they were not directly applicable to the question in hand. This led to their distribution throughout the overall rankings (Table 2) and explains the lack of consensus in opinions.

In response to comments received we have compiled an amended list of potential secondary benefits, more tailored to "implementation-level" decision-making, to be taken forward to Round 3 (see comments below).

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Amended list of potential secondary benefits (Round 3 Q2):

Based on comments received from the panel, we have divided Q2 into two separate parts to take forward to Round 3:

- Firstly, we want to determine the relative value of specific secondary benefits that can be actively built-in to hard coastal defence structures. To address this we have compiled an amended list of *15 potential secondary benefits* (Round 3 Q2a), focusing only on specific design features that can be added to hard structures.
- Secondly, we think that several of the potential benefits included in Round 2 were more relevant to the overall rationale for building-in secondary benefits. Therefore, we have compiled a second list of *10 potential reasons for building-in secondary benefits* (Round 3 Q2b), focusing on the higher-level motivations that would lead to one secondary benefit being prioritised over another.

"Essential considerations" and "primary benefits" have been omitted as they are already accounted for in Q1.

We hope that this approach will allow more meaningful ranking in Round 3.

Defining the context of potential secondary benefits for Round 3:

In this study we are trying to evaluate the potential value of one secondary benefit against another; please remember we are NOT trying to evaluate the presence of coastal defence structures (with or without secondary benefits) against the absence of coastal defence structures (natural shorelines).

Moving forward to Round 3, please place Q2 in the context that the secondary benefits would be actively built-in to hard coastal defence structures above and beyond the design of the structure that would have been used as the status quo, i.e. they are not assumed to be inherent features of hard defence structures.

In Round 3, we ask the panel to consider potential secondary benefits as <u>beneficial features of a hard defence structure evaluated against the same hard defence structure without the added beneficial features.</u> We are NOT asking the panel to consider them as benefits when evaluated against a natural shoreline before the structure was introduced.

For example, in Round 2 some panel members commented that the landscape value of a natural shoreline will not be enhanced by constructing a hard coastal defence, regardless of whether it is a multi-functional structure with built-in benefits or not. Hard coastal defences are widely considered to have a negative impact on natural landscapes. However, the severity of impact on the landscape can be reduced if sensitive design is employed, e.g. by using natural materials or by prioritising aesthetics in the design of the structure. In this context, "Enhanced landscape value" can be thought of as *the value of reducing the negative impact of a structure on the landscape*. This would require actively building-in design features to enhance the landscape value of the structure, e.g. by using natural materials. "Enhanced landscape value" would thus be considered a potential secondary benefit that can be built-in to hard coastal defences.

In Round 3, we also ask the panel to assume that <u>the secondary benefits can be built-in to hard coastal defence structures with no compromise of defence function or additional negative impacts, and further that they can achieve their intended purpose</u>. We are NOT asking the panel to consider the likelihood or current evidence that the secondary benefits will be effective (we acknowledge that lack of evidence is one of the current barriers to moving forward with multi-functional structures; Table 3).

For example, in Round 2, several panel members commented that “Enhanced biosecurity” was unsubstantiated as a potential secondary benefit of coastal defence structures. Artificial structures are widely considered to facilitate the spread of non-native species in the marine environment. However, since this is something of concern across all sectors (“Negative ecological impacts” ranked highest of the non-essential considerations; Table 1), we think it may be of high priority in terms of research and development for ecological engineering solutions in the future. In order to direct research efforts and resources appropriately, we need to first ascertain the theoretical order of priority of desired secondary benefits – even if there is insufficient evidence that those benefits can be realised at present.

We think that Question 2 may provide some of the most interesting and useful findings from this study, but this will only be possible if all panel members respond to Round 3 with this context in mind.

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QUESTION 3

This question investigates whether (and why) you would be more supportive of the construction of additional coastal defences if they were multi-functional structures. We would also like to gather information about the current barriers to implementation and suggestions for moving forward.

From Round 1 responses, we constructed 6 statements to reflect varying levels of support for multi-functional coastal defence structures. In Round 2 the panel were asked to select the one with which they agreed most.

Agreement with statements:

Largely, opinion was divided between statements 5, 4 and 2 (Figure 3). Statement 4 ("I am supportive of the construction of new multi-functional coastal defences, as long as the built-in secondary benefits do not compromise the primary function or cause additional negative impacts" and statement 5 ("I am supportive of the construction of new multi-functional coastal defences, as long as evidence can be provided (in advance) that they will provide significant ecological and/or socio-economic benefits") both reflect caveated support for multi-functional structures as a way forward for coastal defence schemes. Statement 2 ("I do not support the construction of new hard coastal defences, but if new defences are deemed necessary then I would be supportive of them being multi-functional") reflects more general support for multi-functional structures *if* new structures are deemed necessary.

Several panel members indicated that their opinions would be better represented by a combination of 2 or more statements. In particular, statement 4 was frequently referred to as a second choice by those who selected statement 5, and vice versa.

Disagreement with statements:

One panel member from the Statutory Bodies sector selected statement 1 ("I do not support the construction of new hard coastal defences. Multi-functionality would not make me more supportive because overall negative impacts would outweigh any potential secondary benefits."), citing concerns about unsustainable long-term coastal management. However, panel members from the Academic Non-specialist sector, Engineering Consultant sector and Local Authority sector indicated disagreement with this statement, suggesting that in certain scenarios hard defences are necessary and part of the strategic approach to Flood and Coastal Erosion Risk Management (FCERM).

Some panel members also indicated disagreement with statements 6 and 2, again because of the categorical non-support for hard coastal defences, which they did not consider compatible with FCERM in certain scenarios.

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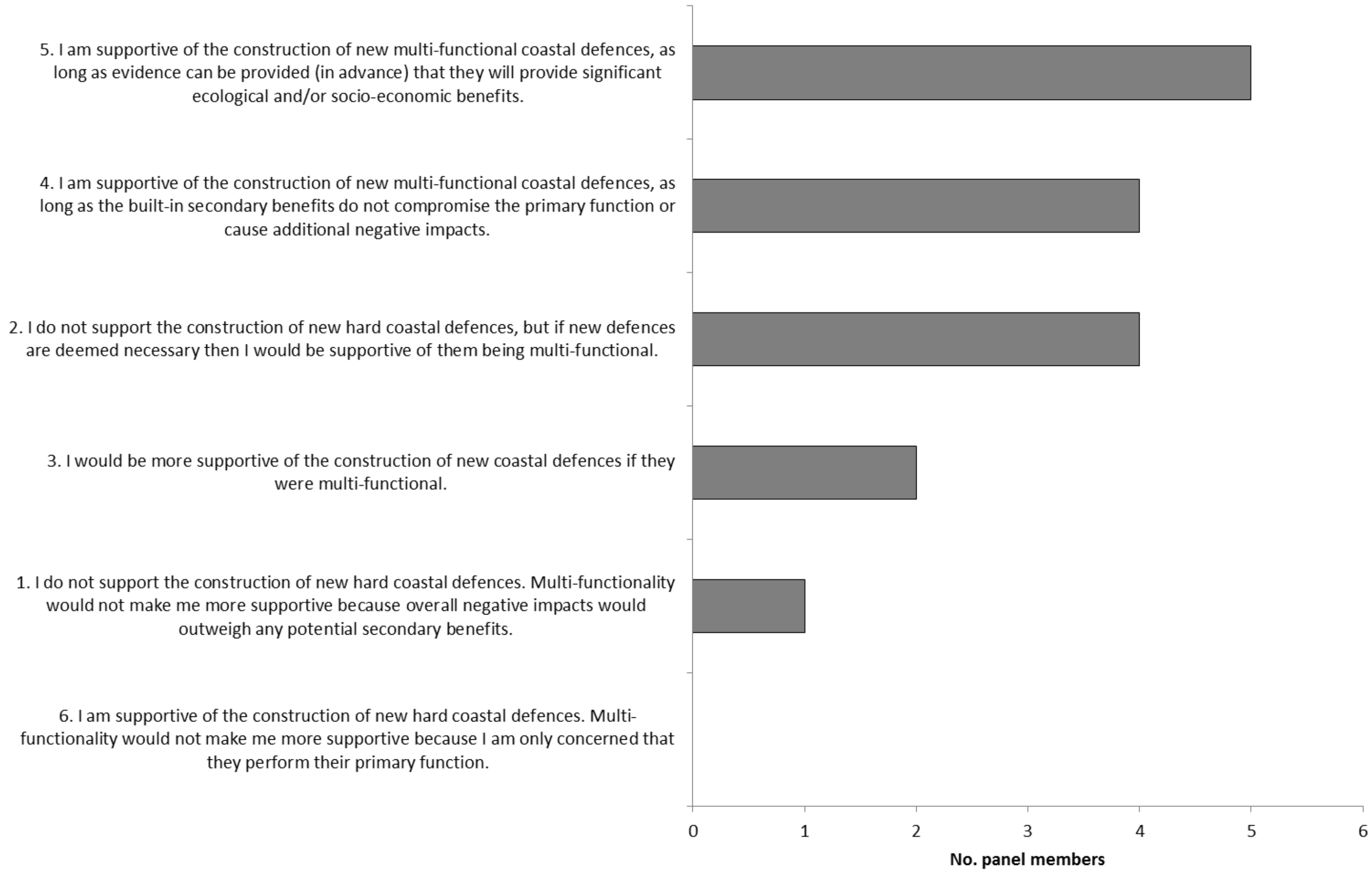

Figure 3 Frequency of selection for each of 6 statements in Round 2 Q3. Panel members were asked to select the statement with which they agreed most.

Moving towards consensus in Round 3:

The divided opinions expressed in Q3 may be because the statements were too strong or specific regarding support or non-support for hard coastal defences. Moving forward to Round 3 we would like to converge towards some level consensus from the panel (although accepting that this will not be achieved if no consensus exists).

We have constructed a new statement which combines elements of the most favoured statements from Round 2 (Round 3 Q3). This new statement does not include any reference to support or non-support of hard coastal defences in general. We acknowledge this is a higher-level debate which is dealt with through strategic FCERM on a case-by-case basis. In Round 3, we again ask the panel to answer Q3 in the context that hard coastal defence structures have been deemed appropriate for a particular shoreline.

We hope that the statement constructed will more closely reflect the opinions of the panel; however we stress that the detailed opinions expressed previously will not be discarded in favour of this more simplified approach. The panel will be invited to comment on this in Round 3.

Current barriers to implementation and suggestions for moving forward:

From Round 1 responses, we compiled a list of 7 current barriers to implementation and 10 suggestions for moving forward with multi-functional coastal defence structures. In Round 2 we asked the panel to rank these in order of priority and make any additions to the 2 lists.

The individual ranks assigned by panel members were again converted to scores[8] which were summed over responses from the whole panel. Total scores were then converted back into overall priority rankings between 1 and 7(10) (1 = high, 7(10) = low) (Table 3).

We received several interesting additions to the lists of current barriers and suggestions for moving forward. We have therefore compiled amended lists to take forward to Round 3 and have not considered rank orders further here.

In response to comments received from the panel we have removed the more extreme and higher-level suggestions for moving forward, i.e. "Make multi-functionality mandatory for new coastal defences" and "We should not move forward with multi-functional structures as this may lead to sacrificing sustainable coastal management for short-term gains". Although these are both valid opinions, we think that they are part of the higher-level debate about strategic FCERM and the extreme division of opinions that they cause may conceal the value of more pragmatic suggestions for moving forward at implementation-level. Again we stress that information received in Round 1 & 2 will not be discarded.

[8] Scores were calculated by subtracting ranks from 21, i.e. inverting ranks 1-20 into more intuitive scores 20-1 (20 = high, 1 = low)

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Table 3 Current barriers to implementation and suggestions for moving forward with multi-functional coastal defence structures in order of priority, as indicated by combined rankings of the panel (1 = high, 7(10) = low)

CURRENT BARRIERS TO EFFECTIVE IMPLEMENTATION	RANK (1-7)
Developments driven by cost and funding priorities	1
Ability to justify additional costs	2
Lack of policy drive	3
Lack of legislative support	4
Reliable assessment of value	5
Lack of evidence that benefits will be realised	6
Awareness of / engagement with the concept of multi-functionality	7
Additional barriers:	
Lack of communication between sectors during planning	
Lack of collaboration with EU partners (missed opportunities for lessons learned)	
Lack of understanding of ecology of manmade habitats	
Lack of well-understood "products" (i.e. ecological engineering solutions)	
SUGGESTIONS FOR MOVING FORWARD	**RANK (1-10)**
Consider multi-functional designs in the planning stage of new defences	1
Strengthen legislative framework	2
Conduct cost-benefit analyses of potential secondary benefits	3
Conduct experimental trials to gather additional evidence	4
Improve awareness and engagement amongst relevant sectors	5
Develop new technologies to improve potential of multi-functional structures	6
Make additional resources available to cover cost of multi-functional features	7
Make multi-functionality mandatory for new coastal defences	8
Expand beneficiary pays principal to include secondary benefits	9
We should not move forward with multi-functional structures as this may lead to sacrificing sustainable coastal management for short-term gains	10
Additional suggestions:	
Collaborate with EU and international partners (knowledge exchange)	
Develop "products" that can be incorporated into scheme designs	
High-level political decisions about what/where will be funded in the lon-term	

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DELPHI STUDY ROUND 3 (FINAL) SYNTHESIS

OVERVIEW

With predicted climate change and increasing coastal development, we anticipate that additional hard sea defences will be necessary around the UK, and that existing defences will need to be maintained. The UK Marine Policy Statement advises that marine developments should not only avoid harm to marine ecology, but may also provide opportunities for building-in 'beneficial features'. In response, there is growing scientific interest in the development of novel *multi-functional* structures that can provide various secondary 'benefits', beyond the primary function of coastal protection.

In Round 1, we asked a panel of 16 experts from 7 different sectors[9] to answer 3 open-ended questions about multi-functional coastal defence structures. In Round 2, we compiled summary lists from the responses received which the panel were asked to rank on a priority scale. In Round 3 we refined the summary lists and constructed 2 summary statements based on feedback received. The panel were again asked to rank the lists on a priority scale and also to indicate their level of agreement with the statements.

In this synthesis report we present the overall order of ranks assigned to each of the considerations, the panel's level of agreement with the 2 statements, and also any consensus/conflicts in opinions across different panel members and sectors. To present a more complete account of perceptions across different sectors, we also present combined *by sector* ranks and include selected quotations, attributed to the sectors with which the quoted panel members are associated. We reiterate that opinions/quotations are not considered *representative* of the sector with which panel members are associated. We further acknowledge that the aggregated (by sector) information presented may not reflect the opinions of all panel members. However, we have endeavoured to avoid misrepresentation of any individual's opinions and have also presented full un-aggregated rankings (by panel member) in graphical figures to communicate variability and outlying opinions. Panel members will be invited to comment on this before any publication of findings.

We acknowledge all comments received regarding the difficulty of such a task and the potential to draw misleading conclusions. Any findings reported from this study will be accompanied by qualifying explanation of the generalisations incorporated into the technique.

[9] The panel comprised experts from the following sectors (numbers in parentheses indicate number of panel members from the sector): Academic Specialist (1), Academic Non-Specialist (2), Ecological Consultant (2), Engineering Consultant (2), Statutory Bodies – Coastal Management & Nature Conservation (5), Local Authority (2) and Conservation (2).

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QUESTION 1

What are the most important considerations when planning coastal defence works (i.e. construction or maintenance of engineered coastal defence structures)?

From Round 2 responses, we reduced the initial list of 20 considerations down to a new list of 10 "implementation-level" considerations that could be meaningfully ranked alongside one another. In Round 3 we asked the panel to rank these, firstly based on the current order of priority given in practice (RANK 1), and secondly, based on what they thought the order of priority *should* be (RANK 2). In reducing the number of considerations in the list, we necessarily forfeited some detail regarding the relative importance of associated positive and negative impacts on ecology and local communities/businesses. We therefore constructed a summary statement to gauge consensus on their relative importance, with which the panel was asked to indicate their level of agreement.

Order of priority:

The individual ranks assigned by panel members were converted to scores[10] which were summed over responses from the whole panel. Total scores were then converted back into overall priority rankings between 1 and 10 (1 = high, 10 = low).

Unsurprisingly, the panel ranked "Essential criteria" as the highest priority consideration when planning coastal defence works, both in terms of current practice and what they thought it should be (Table 1.1). The panel then ranked "Cost", "Net socio-economic impacts on local communities and businesses" and "Net ecological impacts" as the next highest priorities in current practice. These same 3 considerations were also ranked highest when the panel were asked what they thought priorities *should* be; however, they were ranked in a different order. The panel ranked "Net ecological impacts" higher than "Net socio-economic impacts" and both were ranked higher than "Cost".

At the other end of the scale, the panel ranked "Carbon footprint", "Opportunities for research and development" and "Opportunities for education and outreach" as the lowest priorities in current practice. However, the panel indicated that "Carbon footprint" and "Opportunities for research and development" *should* be given higher priority than "Level of community support" and "Net culture and heritage impacts".

[10] Scores were calculated by subtracting ranks from 11, i.e. inverting ranks 1-10 into more intuitive scores 10-1 (10 = high, 1 = low).

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Table 1.1 Considerations for planning coastal defence works in order of priority, as indicated by combined rankings of the panel (1 = high, 10 = low). RANK 1 is based on what the panel thought the current order of priority is in practice; RANK 2 is based on what the panel thought the order of priority *should* be.

CONSIDERATIONS	RANK 1[11] (1-10)	RANK 2 (1-10)
Essential criteria (i.e. part of a sustainable strategy, justification, in line with environmental legislation and planning guidelines, public safety, fit-for-purpose, no unintentional alteration to coastal processes, affordable/funding available)	1	1
Cost (i.e. assuming funding is available)	2	4
Net socio-economic impacts on local communities and businesses (i.e. assuming minimum requirements are met and not including risk reduction from primary defence function: e.g. reduced/enhanced amenity, recreation, fisheries, navigation, tourism, employment, etc.)	3	3
Net ecological impacts (i.e. assuming minimum requirements are met and not including risk reduction from primary defence function: e.g. loss/disturbance of habitats/species, dispersal of invasive non-native species, extraction of raw materials, novel habitat/refuge for exploited species or species of conservation interest, etc.)	4	2
Net landscape impacts (i.e. assuming minimum requirements are met)	5	5
Level of community support (i.e. assuming minimum requirements are met)	6	8
Net culture and heritage impacts (i.e. assuming minimum requirements are met and not including risk reduction from primary defence function: e.g. loss/damage of heritage features or archaeology, platform for art installations, etc.)	7	9
Carbon footprint (i.e. assuming minimum requirements are met: e.g. processing and transport of raw materials, construction emissions, etc.)	8	6
Opportunities for research and development (e.g. new engineering designs, experimental units to investigate marine/coastal ecology)	9	7
Opportunities for education and outreach (e.g. platform for environmental education, etc.)	10	10

[11] Panel members were given the option of not completing RANK 1 if they felt unqualified to do so. Twelve panel members completed RANK 1, four of whom indicated that they felt somewhat unqualified but had provided their "best informed guess". The overall order of priority was the same (Table 1.1) regardless of whether we included or excluded data from these panel members.

Consensus and conflicts in responses:

To investigate the level of consensus amongst the panel, we plotted box and whisker plots showing the median scores, the variation in ranks assigned by different panel members (i.e. interquartile range[12] and max/min scores), and any outlying ranks assigned to each of the 10 considerations (i.e. ranks lying outside 1.5 times the interquartile range) (Figure 1).

There appears to be a relatively high degree of consensus (i.e. smaller interquartile range and shorter whiskers) in the highest and lowest rankings, both in terms of priorities in current practice and (even more so) in preferred priorities. The middle ranks have a varying level of consensus, with more agreement in priorities in current practice than in panel members' preferred priorities. Ranks for "Cost", "Carbon footprint" and "Community support" have very little consensus in terms of preferred priorities.

Looking more closely at the panel's perceptions of how considerations *should* be prioritised (Table 1.2), panel members from the Conservation sector and the Statutory Bodies sector assigned lower ranks to "Cost" than panel members from the other sectors (in fact, panel members from the Conservation sector collectively ranked it as the lowest priority). Comments received suggest that views on "Cost" vary widely, e.g. "I believe all of the considerations listed in Q1 to be of greater importance than the overall cost of the coastal defence works", "in an ideal world the cost of defence structures would not be as important as their primary functionality and their net ecological impacts", "cost is less ambiguous than funding, but it is still sort of fixed and I'm not sure you can rank it", "we are in very challenging financial times and the drivers around any capital spend have to be set against this background".

Whilst ranking "Cost" low, panel members from the Conservation and Statutory Bodies sectors ranked "Carbon footprint" as a higher priority than the rest of the panel, and panellists from the Conservation sector also ranked "Opportunities for education and outreach" (lowest priority overall) higher than the rest of the panel. One panel member from the Statutory Bodies sector supported this perceived importance of education and outreach, suggesting that "we can only change perception of Flood and Coastal Risk Management if education is built in better to schemes".

Interestingly, the Academic Specialist panel member ranked "Opportunities for research and development" as the lowest priority consideration, commenting that although it is their own area of research "I realise that most other factors are more important".

Confidence in the linear rank scale:

Although panel members were not required to provide comment regarding their confidence in ranking in Round 3, several panel members commented that they had more confidence in ranking the new list of 10 considerations than the initial list of 20 in the previous iteration. The panel was given the option of not completing RANK 1 if they felt unqualified to do so. Twelve panel members completed RANK 1, four of whom indicated that they felt somewhat unqualified but had provided their "best informed guess". The overall order of priority was the same (Table 1.1) regardless of whether we included or excluded data from these panel members, so we included them in calculations of median scores and outliers (Figure 1). No concerns were raised regarding confidence in RANK 2.

[12] The interquartile range is calculated as the difference between the 3rd quartile (top edge of boxplot, i.e. middle number between the median and the highest value) and the 1st quartile (bottom edge of the boxplot, i.e. middle number between the median and the lowest value), i.e. the interquartile range contains the middle 50% of the values in the data set.

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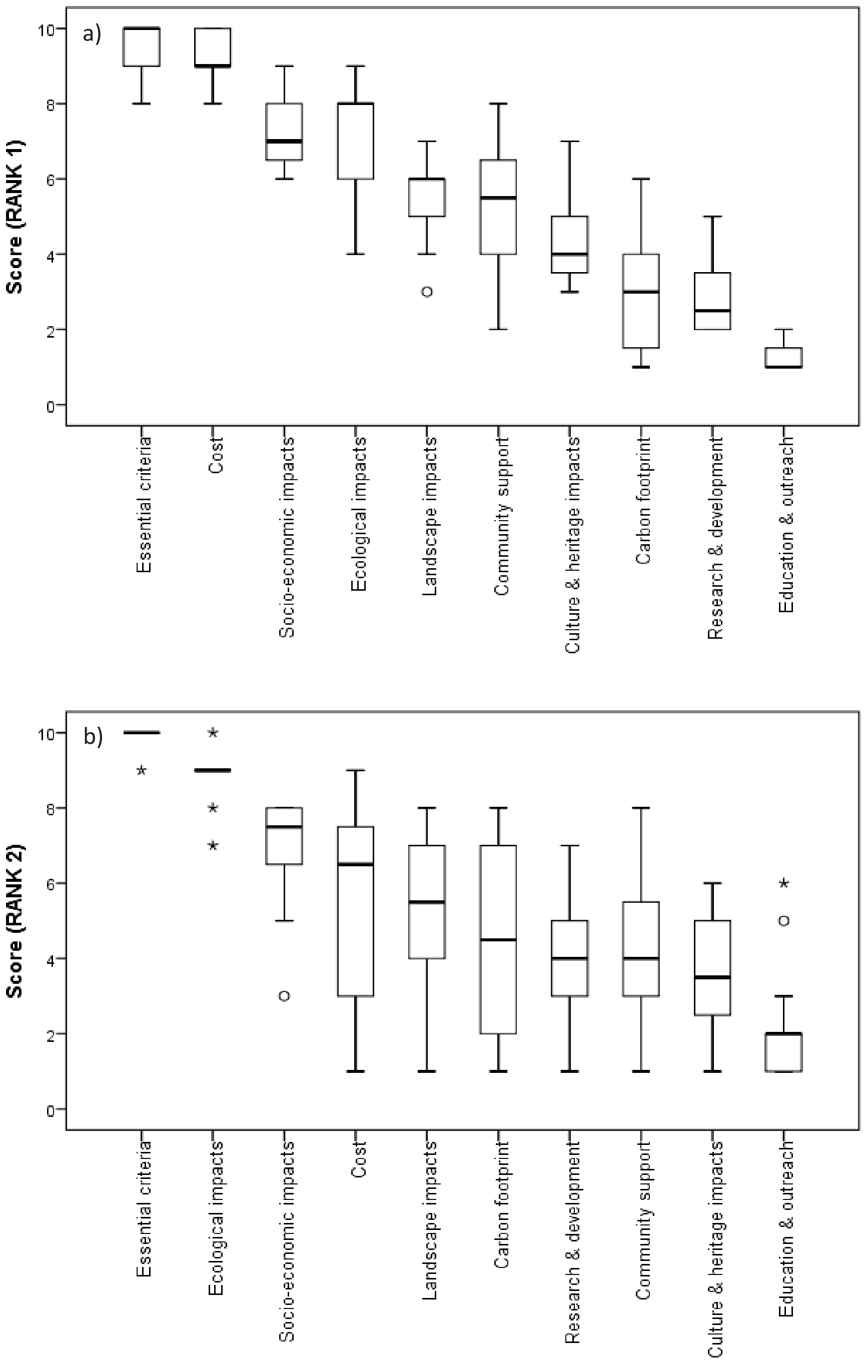

Figure 1 Round 3 Q1 scores assigned by the panel: a) RANK 1 perceived priorities in current practice; b) RANK 2 preferred priorities. Box and whisker plots indicate median scores (mid line), interquartile range (box), max/min ranks (whiskers), outliers (circles) and extreme outliers (stars). Scores were calculated by subtracting ranks from 11, i.e. inverting ranks 1-10 into more intuitive scores 10-1 (10 = high, 1 = low).

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Table 1.2 Considerations for planning coastal defence works in order of preferred priority (i.e. RANK 2), as indicated by combined rankings of panel members from different sectors (1 = high, 10 = low).

CONSIDERATIONS (in order of overall rankings as the panel perceive they should be, i.e. Table 1.1, RANK 2)	**Academic Non-specialist**	**Academic Specialist**	**Conservation**	**Ecological Consultant**	**Engineering Consultant**	**Local Authority**	**Statutory Bodies**
Essential criteria	1	1	1	1	1	1	1
Net ecological impacts	2	2	1	2	2	2	2
Net socio-economic impacts on local communities and businesses	3	3	5	4	3	2	3
Cost	4	4	10	3	3	2	6
Net landscape impacts	5	6	6	5	5	5	5
Carbon footprint	8	8	3	9	7	9	4
Opportunities for research and development	5	10	4	6	7	8	7
Level of community support	7	5	6	6	6	7	9
Net culture and heritage impacts	9	7	6	8	7	5	8
Opportunities for education and outreach	10	9	6	10	10	10	10

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Statement:

The panel were asked to indicate their level of agreement with the following statement:

"*Considerations for avoiding/minimising negative impacts are more important than considerations for creating/maximising positive impacts.*"

Fifteen panel members indicated that they "Agree" or "Strongly Agree" that considerations for avoiding/minimising negative impacts are more important than considerations for creating/maximising positive impacts (Table 1.3). However, some panel members raised concern regarding the generality of the statement, e.g. "certainly for ecology and coastal processes, not sure if this necessarily applies to businesses", "the whole point of implementing a coastal defence is to have a positive impact on humans and the natural environment … you have to demonstrate the positive benefits of a scheme to make it happen, you also know that the negative impacts can bring things to a halt". One panel member from the Statutory Bodies sector indicated that they "Strongly Disagree" with the statement, commenting that "any new structure will have a negative impact, just avoiding/minimising is not really good enough, the aim should be to do something better."

Table 1.3 Level of agreement of panel members from each sector with the statement above.

SECTOR	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
Academic Non-specialist				2	
Academic Specialist					1
Conservation				2	
Ecological Consultant				1	1
Engineering Consultant				1	1
Local Authority				1	1
Statutory Bodies	1			2	2

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QUESTION 2

What are the potential secondary benefits that can be gained from multi-functional coastal defence structures (i.e. beyond their primary function of providing protection against flooding and erosion?)

From Round 2 responses, we reduced the initial list of 20 secondary benefits down to a new list of 15 "implementation-level" secondary benefits that can be actively built-in to hard coastal defence structures. We also compiled a second list of 10 potential reasons for building-in secondary benefits, focusing on the "higher-level" motivations that would lead to one secondary benefit being prioritised over another. The panel were again asked to rank these lists in order of priority.

We asked the panel to consider potential secondary benefits as "beneficial features of a hard defence structure evaluated against the same hard defence structure without the added beneficial features". We also asked the panel to assume that the secondary benefits "can be built-in to hard coastal defence structures with no compromise of defence function or additional negative impacts, and further that they can achieve their intended purpose".

Order of priority:

The individual ranks assigned by panel members were again converted to scores[13] which were summed over responses from the whole panel. Total scores were then converted back into overall priority rankings between 1 and 15(10) (1 = high, 15(10) = low).

Potential secondary benefits

The panel ranked "Habitat for natural rocky shore communities", "Habitat for species of conservation interest" and "Refuge for exploited species" as the highest priority secondary benefits that could be built-in to multi-functional coastal defence structures (Table 2.1). At the other end of the scale, the panel ranked "Opportunities for education and outreach", "Enhanced landscape value" and "Enhanced culture and heritage value" as the lowest priority secondary benefits.

In general, ecological secondary benefits were ranked higher priority than social, economic and technical secondary benefits.

Potential reasons for building-in secondary benefits

The panel ranked "Positive ecological impacts", "Divert pressure from natural systems" and "Positive socio-economic impacts on local communities and businesses" as the highest priority reasons for building-in secondary benefits to coastal defence structures (Table 2.2). At the other end of the scale, the panel ranked "Culture and heritage", "Education and outreach" and "Reduce carbon footprint" as the lowest priority reasons.

There is logical agreement between the highest ranked motivations for building-in secondary benefits (i.e. create/maximise positive ecological impacts and divert pressure from adjacent natural habitats) and the highest priority secondary benefits (i.e. ecologically-beneficial features). Similar agreement is also apparent between the lowest ranked benefits and reasons.

[13] Scores were calculated by subtracting ranks from 16(11), i.e. inverting ranks 1-15(10) into more intuitive scores 15(10)-1 (15(10) = high, 1 = low).

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Table 2.1 Potential secondary benefits that can be built-in to multi-functional coastal defence structures in order of priority, as indicated by combined rankings of the panel (1 = high, 15 = low)

POTENTIAL SECONDARY BENEFIT DESIGN FEATURES	RANK (1-15)
Habitat for natural rocky shore communities (e.g. build-in microhabitat complexity and use materials suitable for natural rocky shore communities to colonise)	1
Habitat for species of conservation interest (e.g. build-in habitat suitable for wintering birds, BAP species, etc.)	2
Refuge for exploited species (e.g. build-in refuge habitat suitable for exploited species to allow populations to persist)	3
Habitat heterogeneity in structure design (e.g. build-in mosaic of habitats such as rocky substrate, sediments, saltmarsh patches, etc.)	4
Enhanced commercial fisheries (e.g. build-in refuge/nursery habitat for commercial species)	5
Safeguarded biosecurity (e.g. build-in features to remove/reduce competitive advantage of non-native invasive species)	6
Enhanced amenity/recreation (e.g. build-in surf reef design, promenade, beach access, recreational fishing platform, etc.)	7
House other technologies (e.g. build-in turbines, masts, etc.)	7
Mariculture opportunities (e.g. build-in facilities for mussel/macroalgae culture)	9
Reduced carbon footprint (e.g. use novel low-carbon materials or recycled waste materials)	10
Opportunities for research and development – new engineering solutions (e.g. trial novel materials and structural designs)	11
Opportunities for research and development – investigating marine/coastal ecology (e.g. build-in experimental mesocosm units)	12
Enhanced landscape value (e.g. use natural materials, subtle design or aesthetically-attractive design)	13
Opportunities for education and outreach (e.g. build-in facilities for public engagement or environmental education)	14
Enhanced culture and heritage value (e.g. build-in art installations)	15

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Table 2.2 Potential reasons for building-in secondary benefits to coastal defence structures in order of priority, as indicated by combined rankings of the panel (1 = high, 10 = low)

REASONS FOR BUILDING-IN SECONDARY BENEFITS	RANK (1-10)
Positive ecological impacts (i.e. through enhanced connectivity/resilience of rocky habitats, habitat for exploited species, habitat for species of conservation concern, habitat heterogeneity, etc.)	1
Divert pressure from natural systems (i.e. by providing access for recreation, fisheries, research, co-location with other technologies etc.)	2
Positive socio-economic impacts on local communities and businesses (i.e. through enhanced amenity, recreation, fisheries, navigation, tourism, employment, etc.)	3
Increase likelihood of scheme progression (i.e. by fostering public support and improving partnership funding potential)	4
Reduce maintenance requirements (i.e. by building-in positive feedback in stability of structure)	5
Research and development (i.e. gather evidence necessary for moving forward with multi-functional coastal defences by trialling novel engineering designs and improving knowledge of marine/coastal ecology)	6
Enhance/safeguard landscape (i.e. by using natural materials, subtle design or aesthetically-attractive design)	7
Reduce carbon footprint (i.e. by using low carbon technology, recycled materials, etc.)	8
Education and outreach (i.e. by building-in facilities for public engagement and environmental education)	9
Culture and heritage (i.e. by building-in art installations, etc.)	10

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Consensus and conflicts in responses:

To investigate the level of consensus amongst the panel, we again plotted box and whisker plots showing the median scores, the variation in ranks assigned by different panel members (i.e. interquartile range[14] and max/min scores), and any outlying ranks assigned to each of the 15 secondary benefits and 10 reasons for building them into structures (i.e. ranks lying outside 1.5 times the interquartile range) (Figure 2).

There appears to be reasonable consensus in the highest and lowest ranked secondary benefits and reasons for building them into developments (i.e. small interquartile ranges and/or short whiskers). However, there was little agreement regarding the middle ranks.

<u>Potential secondary benefits</u>

The Academic Specialist assigned the top ranks differently to the rest of the panel, prioritising socio-economic and technical benefits (i.e. "Enhanced amenity/recreation", "House other technologies" and "Enhanced commercial fisheries") above the more direct ecological benefits (Table 2.3). They commented that "when it comes to building in actual benefits, the socio[-economic] ones are of higher priority, partly because the ecological ones can be built in around [them]".

Panel members from the Local Authority and Engineering Consultant sectors also ranked "Enhanced amenity/recreation" high, whereas those from the Conservation and Statutory Bodies sectors ranked this particularly low. Panel members from the Conservation sector instead ranked "Safeguarded biosecurity" high, as did those from the Academic Specialist and Ecological Consultant sectors, whereas the Engineering Consultants ranked this as their lowest priority. Panellists from the Engineering Consultant sector also ranked "Refuge for exploited species" lower than the rest of the panel, but instead prioritised "Reduced carbon footprint" and "Enhanced landscape value".

Finally, panel members from the Academic Non-specialist and Statutory Bodies sectors ranked "Mariculture opportunities" higher than the panel as a whole. Some panel members considered this as an opportunity for co-location of marine activities, akin to "House other technologies", and ranked it high "given the increasingly busy state of the seas". However, other panellists were sceptical of the viability of this secondary benefit "due to differences in the scale of the operation and the optimal location for such activities", and raised concern about "introductions of species novel to the system". This latter concern was shared by several panel members in relation to some of the highest ranking ecological benefits, i.e. "Habitat for natural rocky shore communities", "Habitat for species of conservation interest" and "Habitat heterogeneity in structure design". The importance of site-specific decision-making has been a clear message throughout this process, i.e. any potential ecological benefits must be evaluated in the context of local natural habitats.

<u>Potential reasons for building-in secondary benefits</u>

Panel members from the Engineering Consultant and Local Authority sectors assigned their highest ranks differently to the rest of the panel, i.e. "Reduce maintenance requirements" and "Increase likelihood of scheme progression", respectively (Table 2.4). However, panellists from both sectors ranked "Positive

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[14] The interquartile range is calculated as the difference between the 3rd quartile (top edge of boxplot, i.e. middle number between the median and the highest value) and the 1st quartile (bottom edge of the boxplot, i.e. middle number between the median and the lowest value). Thus, the interquartile range contains the middle 50% of the values in the data set.

ecological impacts" and "Positive socio-economic impacts on local communities and businesses" joint second, indicating agreement with the overall panel perception that these are primary motivations for building-in secondary benefits.

Conversely, panel members from the Conservation and Ecological Consultant sectors assigned particularly low priority to "Increase likelihood of scheme progression". One panel member commented that "if a defence structure is being planned it is a necessity in whatever form decided upon … therefore, I believe it is not a case that it will progress any faster/smoother as a result of added enhancements". Panellists from the Conservation sector also ranked "Positive socio-economic impacts on local communities and businesses" much lower than the rest of the panel. Instead they prioritised "Reduce carbon footprint", "Research and development" and "Education and Outreach". Academic Non-specialists and Ecological Consultants also ranked "Research and development" higher than the rest of the panel, whereas the Academic Specialist again ranked this low.

There was little agreement in ranks assigned to "Enhance/safeguard landscape"; although panel members from the Academic Non-specialist, Ecological Consultant and Statutory Bodies sectors ranked it fairly high, it was ranked last by the Academic Specialist as they felt "it is not really a secondary benefit". Also at the bottom of the rankings, "Culture and heritage" and "Education and outreach" have been consistently perceived as low priority considerations for secondary benefits throughout this process. Rationale for this was provided by some panel members, including that there are more appropriate places to cater for these activities, and also that it is difficult to value them and identify a beneficiary through which to balance associated costs. In Round 2, one panel member commented that the lack of representation from these sectors on the panel may lead to negative bias in their ranking. The size of the panel was restricted in favour of improving the likelihood of maintaining 100% (and balanced) participation throughout the process. However, this will be acknowledged as a limitation of the study.

Confidence in the linear rank scale:

Levels of confidence in the rankings varied considerably. There was generally greater confidence in rankings assigned to the second part of the question (i.e. potential reasons for building-in secondary benefits), following in-depth consideration during Rounds 1 & 2. Some panel members indicated that the task was easier than the previous iteration because there were fewer benefits and reasons to consider. However, several panel members again reported uncertainty, either because they felt benefits were inherently linked or were of equal importance, or because of uncertainty when trying to evaluate potential benefits, or because of the importance of case-specific assessment. One panel member also commented on the difficulty of assessing the importance of secondary benefits when sceptical about their feasibility.

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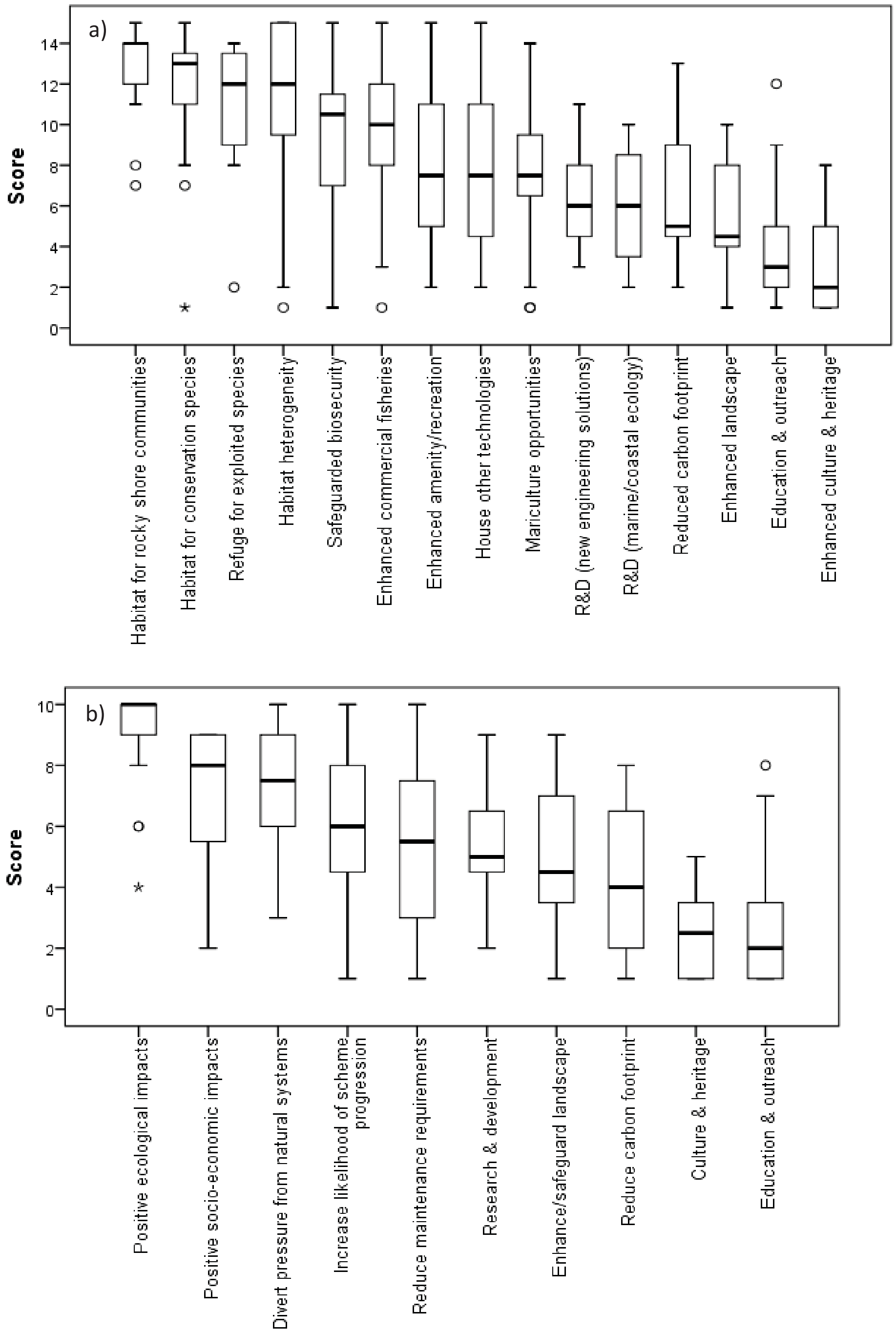

Figure 2 Round 3 Q2 scores assigned by the panel: a) potential secondary benefits; b) reasons for building-in benefits. Box and whisker plots indicate median scores (mid line), interquartile range (box), max/min ranks (whiskers), outliers (circles) and extreme outliers (stars). Scores were calculated by subtracting ranks from 16(11), i.e. inverting ranks 1-15(10) into more intuitive scores 15(10)-1 (15(10) = high, 1 = low).

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Table 2.3 Potential secondary benefits that can be built-in to multi-functional coastal defence structures in order of priority, as indicated by combined rankings of panel members from different sectors (1 = high, 15 = low)

POTENTIAL SECONDARY BENEFITS (in order of overall rankings assigned by the panel)	Academic Non-specialist	Academic Specialist	Conservation	Ecological Consultant	Engineering Consultant	Local Authority	Statutory Bodies
Habitat for natural rocky shore communities	2	9	4	1	1	5	1
Habitat for species of conservation interest	4	5	1	5	1	2	3
Refuge for exploited species	4	7	1	2	9	6	2
Habitat heterogeneity in structure design	1	6	5	2	4	3	5
Enhanced commercial fisheries	3	3	7	6	5	3	8
Safeguarded biosecurity	8	4	3	4	15	7	7
Enhanced amenity/recreation	10	1	13	8	3	1	12
House other technologies	11	2	8	6	9	8	6
Mariculture opportunities	4	8	10	13	13	9	4
Reduced carbon footprint	12	11	8	11	5	14	9
Opportunities for research and development – new engineering solutions	7	10	11	11	8	10	13
Opportunities for research and development – investigating marine/coastal ecology	8	14	6	10	11	11	13
Enhanced landscape value	13	15	14	8	5	11	10
Opportunities for education and outreach	14	13	11	14	13	15	11
Enhanced culture and heritage value	14	12	15	15	12	13	15

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Table 2.4 Potential reasons for building-in secondary benefits to coastal defence structures in order of priority, as indicated by combined rankings of panel members from different sectors (1 = high, 10 = low)

REASONS FOR BUILDING-IN BENEFITS (in order of overall rankings assigned by the panel)	Academic Non-specialist	Academic Specialist	Conservation	Ecological Consultant	Engineering Consultant	Local Authority	Statutory Bodies
Positive ecological impacts	1	3	1	1	2	2	1
Divert pressure from natural systems	2	1	2	2	5	4	4
Positive socio-economic impacts on local communities and businesses	2	2	8	3	2	2	2
Increase likelihood of scheme progression	4	5	7	9	4	1	5
Reduce maintenance requirements	7	4	6	6	1	5	8
Research and development	4	9	4	4	6	6	6
Enhance/safeguard landscape	4	10	9	5	6	7	2
Reduce carbon footprint	9	6	2	6	8	9	7
Education and outreach	9	8	5	8	10	10	9
Culture and heritage	8	7	10	10	9	7	10

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QUESTION 3

This question investigates whether (and why) you would be more supportive of the construction of additional coastal defences if they were multi-functional structures. We would also like to gather information about the current barriers to implementation and suggestions for moving forward.

From Round 2 responses, we constructed a summary statement which combined elements of the most favoured statements from Round 2, in an effort to converge towards some consensus from the panel (although accepting that this would not be achieved if no consensus exists). We also compiled amended lists of 10 barriers to implementation and 10 suggestions for moving forward, removing some of the more extreme and higher-level suggestions, but including some useful additions raised in Round 2. The panel were asked to indicate their level of agreement with the summary statement and to rank the lists in order of priority.

Statement:

The panel were asked to indicate their level of agreement with the following statement:

"*Where hard coastal defence structures are deemed necessary, I would be more supportive of them being multi-functional structures, as long as:*

- *built-in secondary benefits do not compromise primary defence function or cause additional negative impacts, and*
- *evidence can be provided that intended ecological and/or socio-economic benefits will be realised.*"

Fifteen panel members indicated that they "Agree" or "Strongly Agree" that they would be more supportive of hard coastal defence structures (where they are deemed necessary) being multi-functional structures, as long as the 2 assumptions above were satisfied (Table 3.1). One panel member from the Engineering Consultant sector selected "Neither Agree nor Disagree", commenting that "it is important to demonstrate that there is a benefit from an engineering perspective too, some positive feedback that makes the structure perform better". Two panel members (from the Local Authority and Statutory Bodies sectors) also felt that the statement should specify that "the secondary benefits should be of a reasonable cost" and that any additional cost would need to be "in proportion to the effect/evidence". Conversely, 3 panellists (from the Conservation, Academic Non-specialist and Statutory Bodies sectors) felt that the statement was too constrained by the need to provide evidence which may be an unreasonable obstacle to implementation. It was suggested that "there will always be a level of uncertainty" but that this "should not be a reason NOT to design structures with secondary aims in mind". Instead, "there should be a presumption that there will be some positive effect" based on existing evidence from other areas.

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Table 3.1 Level of agreement of panel members from each sector with the statement above.

SECTOR	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
Academic Non-specialist				1	1
Academic Specialist					1
Conservation				2	
Ecological Consultant				1	1
Engineering Consultant			1		1
Local Authority					2
Statutory Bodies				2	3

Order of priority:

The individual ranks assigned by panel members were again converted to scores[15] which were summed over responses from the whole panel. Total scores were then converted back into overall priority rankings between 1 and 10 (1 = high, 10 = low).

<u>Current barriers to effective implementation</u>

The panel ranked "Developments driven by cost and funding", "Lack of policy drive and legislative support", "Ability to justify additional costs" and "Reliable assessment of value" as the greatest barriers to effective implementation of secondary benefits (Table 3.2). At the other end of the scale, the panel ranked "Lack of collaboration with EU/international partners", "Lack of understanding of ecology of manmade habitats" and "Lack of well-understood products" as the barriers of least concern.

<u>Suggestions for moving forward</u>

The panel ranked "Consider multi-functional designs in the planning stage of new defences", "Strengthen legislative framework" and "Conduct cost-benefit analyses of potential secondary benefits" as the highest priority suggestions for moving forward (Table 3.2). At the other end of the scale, the panel ranked "Collaborate with EU/international partners", "Expand beneficiary pays principal to include secondary benefits", "Develop new technologies to improve potential of multi-functional structures" and "Develop products that can be incorporated into scheme designs" as the lowest priority suggestions.

Consensus and conflicts in responses / Confidence in the linear rank scale:

To investigate the level of consensus amongst the panel, we again plotted box and whisker plots showing the median scores, the variation in ranks assigned by different panel members (i.e. interquartile range[16] and

[15] Scores were calculated by subtracting ranks from 11, i.e. inverting ranks 1-10 into more intuitive scores 10-1 (10 = high, 1 = low).
[16] The interquartile range is calculated as the difference between the 3rd quartile (top edge of boxplot, i.e. middle number between the median and the highest value) and the 1st quartile (bottom edge of the boxplot, i.e. middle number between the median and the lowest value). Thus, the interquartile range contains the middle 50% of the values in the data set.

max/min scores), and any outlying ranks assigned to each of the 10 current barriers and 10 suggestions for moving forward (i.e. ranks lying outside 1.5 times the interquartile range) (Figure 3).

There appears to be very little consensus in the panel regarding both the current barriers to implementation and the suggestions for moving forward (i.e. large interquartile ranges and/or long whiskers). Several panel members stated that they perceive all of the barriers and suggestions for moving forward to be important, and so found them difficult to rank meaningfully. Others commented that they found it more logical to rank the suggestions for moving forward in the order that they should be addressed temporally, rather than in terms of their relative importance. We found this a helpful way of organising our synthesis of the discourse here, rather than making any further comment regarding different priorities across sectors.

Steps to effective implementation:

Step 1: Gather evidence of efficacy of secondary benefits

Several panel members commented that a lot of evidence currently exists to support the implementation of certain secondary benefits, and also that the ecology of manmade habitats was relatively well understood. However, there was still concern that "Lack of evidence" (and awareness of it) is currently a barrier to increasing "Policy drive and legislative support" and "Awareness and engagement with the concept of multi-functionality". Therefore, it was suggested that the first step forward should be a systematic evidence-gathering exercise, which would involve firstly collating existing evidence from the literature and "Collaboration/knowledge exchange with international/EU partners", and secondly filling any knowledge gaps by "Conducting experimental trials".

Step 2: Value secondary benefits

The "Ability to justify additional costs" and to make a "Reliable assessment of value" of potential secondary benefits were perceived barriers to implementation. It was suggested that there are tools available for making such assessments (but that these needed further development), and that it is important to "Conduct cost-benefit analyses" to make effective valuations of the net benefits of different options. It was also suggested that it would then be necessary to identify potential beneficiaries (which could include UK PLC) in order to attract necessary funding for secondary benefits (i.e. "Expand beneficiary pays principal" and "Make additional resources available to cover cost of multi-functional features").

Step 3: Develop new technologies and ecological engineering "products"

Although "Lack of ecological engineering products" and "Develop products that can be incorporated into designs" were both ranked relatively low (according to one panel member this was because they believe products already exist), this would be the next logical step in the progression to implementation. Several panel members (from the Engineering Consultant, Statutory Bodies, Academic Non-specialist and Academic Specialist sectors) ranked "Develop ecological engineering products", "Develop new technologies" and "Conduct experimental trials" as high priorities for moving forward, despite not ranking "Research and development" as a high priority secondary benefit or motivation for building-in benefits in Q2.

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Step 4: Encourage implementation

It was suggested by some panel members that the legislative framework, communication between sectors and awareness of multi-functional structures all exist, but that what is lacking is the robust evidence to drive policy changes, and encourage engagement with the concept of multi-functionality and communication during the planning process. If Steps 1-3 can be achieved, then it was suggested that more specific policy may develop to "Strengthen the legislative framework" in which secondary benefits are considered. This would be the strongest driver to implementation and justify any additional costs. This would provide the incentive and confidence required to "Improve awareness and engagement amongst relevant sectors" and encourage more communication between sectors about available options. Most panel members agreed that it is vital that secondary benefits are "Considered in the planning stage of new defences".

Existing evidence base (*comments from the researchers*)

Although the sequence above logically describes the perceived steps that are necessary to effective and wide-scale implementation of multi-functional coastal defence structures, it is important to note that we are not starting from the beginning of Step 1. Several panel members stressed that much general evidence already exists globally to support methods of enhancing artificial structures for environmental, social and economic benefit. However, it is unrealistic to expect practitioners across different sectors to keep abreast of the rapidly-expanding body of academic literature in this field. Instead, it may be necessary for academics to pro-actively facilitate knowledge exchange and uptake through training sessions and practitioner-focused workshops, such as the URBANE Project Final Stakeholder Workshop that took place in June 2013 (http://urbaneproject.org/final-stakeholder-workshop).

The Academic Specialist on our panel commented that "thankfully we are now sitting on a wealth of proof-of-concept studies and word is getting out [but] the field is so much in its infancy that we need to actually communicate the possibilities before we can really get the opportunities to do more testing". This view is supported by comments by panel members from the Statutory Bodies, Ecological Consultant and Conservation sectors (as well as similar appeals in the peer-reviewed literature): the perceived lack of evidence mustn't be an obstacle to implementation, indeed implementation (with experimental control and long-term monitoring) is necessary in order to gather further evidence.

If panel members (or their colleagues/organisations) would be interested in receiving further information regarding the evidence base for ecological engineering and its application in coastal defence developments, please do not hesitate to ask. We would be more than happy to compile useful references and/or consider possibilities for further discussions/information-sharing.

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Table 3.2 Current barriers to implementation and suggestions for moving forward with multi-functional coastal defence structures in order of priority, as indicated by combined rankings of the panel (1 = high, 10 = low)

CURRENT BARRIERS TO EFFECTIVE IMPLEMENTATION	RANK (1-10)
Developments driven by cost and funding priorities	1
Lack of policy drive and legislative support	2
Ability to justify additional costs	3
Reliable assessment of value	4
Awareness of / engagement with the concept of multi-functionality	5
Lack of evidence that benefits will be realised	6
Poor communication between sectors during planning	7
Lack of well-understood "products" (i.e. ecological engineering solutions)	8
Lack of understanding of ecology of manmade habitats	9
Lack of collaboration with EU/international partners (i.e. knowledge exchange)	10
SUGGESTIONS FOR MOVING FORWARD	**RANK (1-10)**
Consider multi-functional designs in the planning stage of new defences	1
Strengthen legislative framework	2
Conduct cost-benefit analyses of potential secondary benefits	3
Conduct experimental trials to gather additional evidence	4
Make additional resources available to cover cost of multi-functional features	5
Improve awareness and engagement amongst relevant sectors	6
Develop "products" that can be incorporated into scheme designs	7
Develop new technologies to improve potential of multi-functional structures	7
Expand beneficiary pays principal to include secondary benefits	9
Collaborate with EU/international partners (knowledge exchange)	10

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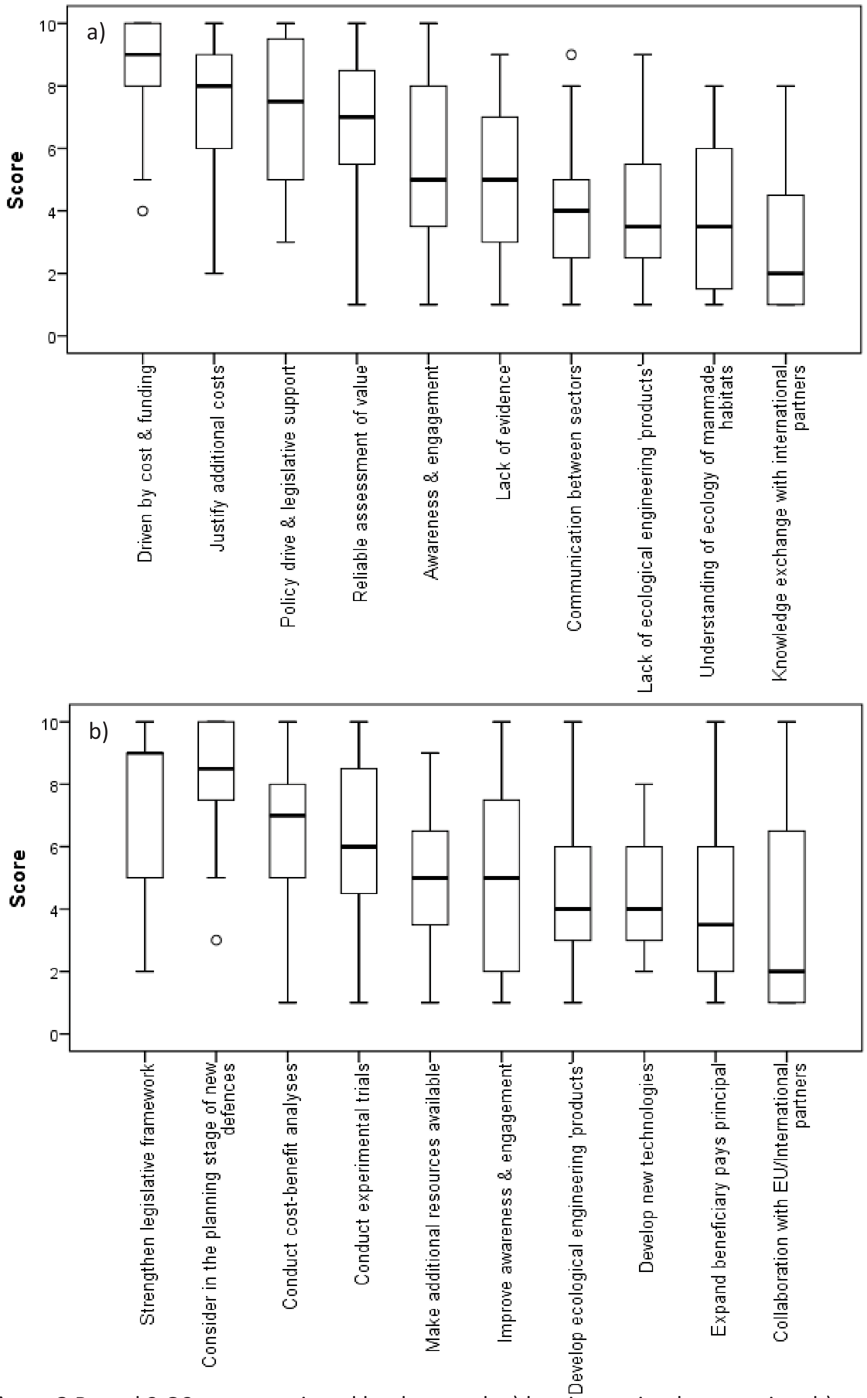

Figure 3 Round 3 Q3 scores assigned by the panel: a) barriers to implementation; b) suggestions for moving forward. Box and whisker plots indicate median scores (mid line), interquartile range (box), max/min ranks (whiskers), outliers (circles) and extreme outliers (stars). Scores were calculated by subtracting ranks from 11, i.e. inverting ranks 1-10 into more intuitive scores 10-1 (10 = high, 1 = low).

Appendix XI

Questionnaire Survey Results

Questionnaire Survey Results

(See Appendix VII for Questionnaire document)

Question 1: *What is the* ***primary purpose*** *of coastal defence structures?*
Question 2: *What are the* ***secondary purposes*** *of coastal defence structures?*

The majority of respondents selected 'Protect against flooding and erosion' as the primary purpose of coastal defence structures (selected by 87.3% of respondents), whilst a small proportion selected 'Stabilise the coastline' (13.6%) (Table 1). The most frequently-selected secondary purposes were 'Stabilise the coastline' (69.5%), 'Increase amenity value / access for recreation' (39.0%) and 'Provide hard substrate for marine life to colonise' (28.0%) (Table 2).

Perceptions were consistent across different sector groups (Pseudo-$F_{7,117}$ = 1.033, P(perm) = 0.418). However, in some sectors (i.e. Engineering Consultant, Local Authority and Statutory Bodies), 'Protect against flooding and erosion' and 'Provide refuge for commercial fisheries species' were not perceived as secondary purposes. The Statutory Bodies and Engineering Consultants also did not select 'Provide substrate for mariculture of commercial species' as a secondary purpose. Engineering Consultants further did not select 'Provide substrate for marine life to colonise' and Local Authorities did not select 'Increase landscape value'.

The following 'Other' secondary purposes were proposed:

- Habitat for roosting birds
- Protect freshwater habitats
- Maintain existing environmental balance
- None

Table 1 Frequency of selection (% of responses) of the perceived primary purpose of coastal defence structures, as indicated by questionnaire responses (n = 118). Respondents were asked to select one option only.

PRIMARY PURPOSE	All Sectors	ANS	AS	C	EcC	EnC	LA	P	SB
Protect against flooding & erosion	87.3	80.0	80.0	78.6	86.7	100	100	89.2	94.1
Stabilise the coastline	13.6	20.0	20.0	21.4	13.3	0	0	13.5	5.9
Habitat for marine life	0	0	0	0	0	0	0	0	0
Substrate for mariculture	0	0	0	0	0	0	0	0	0
Refuge for commercial species	0	0	0	0	0	0	0	0	0
Acces for amenity & recreation	0	0	0	0	0	0	0	0	0
Landscape value	0	0	0	0	0	0	0	0	0

Table 2 Frequency of selection (% of responses) of the perceived secondary purposes of coastal defence structures, as indicated by questionnaire responses (n = 118). Respondents were asked to select all that apply.

SECONDARY PURPOSES	All Sectors	ANS	AS	C	EcC	EnC	LA	P	SB
Stabilise coast	69.5	65.0	80.0	71.4	80.0	83.3	80.0	59.5	75.0
Access for amenity & recreation	39.0	30.0	60.0	35.7	20.0	50.0	100	46.0	25.0
Habitat for marine life	28.0	35.0	20.0	28.6	26.7	0	60.0	35.1	6.3
Protect against flooding & erosion	17.0	25.0	20.0	28.6	26.7	0	0	16.2	0
Landscape value	16.1	15.0	20.0	7.1	20.0	16.7	0.0	21.6	12.5
Substrate for mariculture	14.4	10.0	20.0	14.3	20.0	0	20.0	21.6	0
Refuge for commercial species	13.6	5.0	20.0	21.4	20.0	0	0	21.6	0

Question 3: *What are the potential* ***benefits*** *(not purpose) of coastal defence structures?*
Question 4: *What are the potential* ***negative impacts*** *of coastal defence structures?*
Question 5: *What are the* ***most important considerations*** *when planning coastal defence works?*

When asked about the potential benefits, negative impacts and most important considerations for planning coastal defences, there were significant differences in responses from different sectors (Pseudo-$F_{7,117}$ = 1.420, *P*(perm) = 0.037).

Engineering Consultant perceptions differed significantly to those of Academic Non-specialists (t = 1.844, *P*(perm) = 0.006), Conservationists (t = 1.56, *P*(perm) = 0.028), Ecological Consultants (t = 1.976, *P*(perm) = 0.001), the Public (t = 1.626, *P*(perm) = 0.012) and Statutory Bodies (t = 2.193, *P*(perm) = 0.001). Responses from the Statutory Bodies sector also differed to Local Authorities (t = 1.569, *P*(perm) = 0.030) and members of the Public (t = 1.460, *P*(perm) = 0.037).

Overall, questionnaire respondents ranked 'Provide hard substrate for marine life to colonise', 'Protect against flooding and erosion' and 'Stabilise the coastline' as the most important potential benefits of coastal defence structures (Table 3). At the other end of the scale, they ranked 'Increase landscape value' and 'Provide substrate for mariculture of commercial species' as the least important. However, respondents from the Engineering Consultant sector perceived 'Increase landscape value' as one of the most important potential benefits, and did not rank 'Provide substrate for marine life to colonise' high. Respondents from the Statutory Bodies and Conservation sectors perceived 'Provide refuge for commercial fisheries species' as more important than those from other sectors.

Table 3 Potential benefits of coastal defence structures in order of importance, as indicated by combined ranks of questionnaire respondents and by combined ranks of respondents from different sectors. Respondents were asked to rank 5 options on a scale of importance (1 = most important, 5 = least important).

POTENTIAL BENEFITS	All Sectors	ANS	AS	C	EcC	EnC	LA	P	SB
Provide substrate for marine life	1	1	1	2	1=	5	1	2	1
Protect against flooding & erosion	2	2	2	1	1=	4	2	1	4
Stabilise the coastline	3	3	4	4	3	1	4=	3	6
Access for amenity & recreation	4	4=	3	5	6	2=	3	4	3
Refuge for commercial species	5	6	6	3	4	6	4=	6	2
Provide substrate for mariculture	6	4=	5	6	5	7	6	5	5
Increase landscape value	7	7	7	7	7	2=	7	7	7

Overall, respondents ranked 'Alter natural coastal processes', 'Degrade the natural environment' and 'Spoil the landscape' as the most important negative impacts of coastal defence structures (Table 4). Few respondents selected 'They do not cause any negative impacts' (2.5%), whilst a slightly higher proportion selected 'Their importance for protecting the coast outweighs any negative impact' (8.5%). One Engineering Consultant argued that "*the importance for protection should easily outweigh the negative impacts; otherwise we should question the need for the structure*" *(EnC)*.

Table 4 Potential negative impacts of coastal defence structures in order of importance, as indicated by combined ranks of questionnaire respondents and by combined ranks of respondents from different sectors. Respondents were asked to rank 5 options on a scale of 1 to 5 (1 = most important, 5 = least important).

n/s: not selected

POTENTIAL NEGATIVE IMPACTS	All Sectors	ANS	AS	C	EcC	EnC	LA	P	SB
Alter natural coastal processes	1	1	1	1	1	1=	1	1	1
Degrade natural environment	2	2	2=	2	2	1=	2=	3	2
Spoil landscape	3	3	2=	3=	4=	3	4	2	6
Expensive	4	4	6=	3=	4=	4=	2=	4	5
Spread of non-native species	5	5=	5	5	3	7	8	5	3
Colonisation of non-natural assemblages	6	5=	4	6	6	8	9	6	4
Dangerous	7	7	6=	n/s	7	4=	7	8	7
None – importance outweighs negative impacts	8	8	n/s	7	8	6	5=	7	8
None – no negative impacts	9	n/s	n/s	n/s	n/s	n/s	5=	9	n/s

The most important considerations for planning coastal defence works were perceived to be their 'Defence function', 'Environmental impact' and 'Longevity' (Table 5). At the other end of the scale, 'Impact on tourism' and 'Local public support' received the lowest ranks. No respondents from the Engineering Consultant sector included 'Carbon footprint' or 'Biotic colonisation' in the five most important considerations. They did, however, perceive 'Amenity value' to be more important than other respondents. Local Authority respondents omitted ‘Biotic colonisation’ and ‘Impact on tourism’ from their top priorities.

Table 5 Considerations for planning coastal defence works in order of importance, as indicated by combined ranks of questionnaire respondents and by combined ranks of respondents from different sectors. Respondents were asked to rank 5 options on a scale of 1 to 5 (1 = most important, 5 = least important).

n/s: not selected

CONSIDERATIONS	All Sectors	ANS	AS	C	EcC	EnC	LA	P	SB
Defence function	1	1	1	1	2	1	1	2	1=
Environmental impact	2	2	2	2	1	2=	3	1	1=
Longevity	3	3	4	3	3	4	2	3	3
Cost	4	4	3	4	4	2=	4	4	4
Visual impact	5	5=	7	5=	5	8	5	6	7
Carbon footprint	6	7	5=	7	7	n/s	6=	5	5
Biotic colonisation	7	5=	5=	5=	6	n/s	n/s	7	6
Amenity value	8=	10	9=	9	9	5	6=	8=	8
Local public support	8=	9	8	8	10	6=	6=	8=	10
Impact on tourism	10	8	9=	10	8	6=	n/s	10	9

The following ‘Other’ potential benefits were proposed:

- Co-location of wave turbines
- Mitigate habitat loss elsewhere
- Enhance connectivity between hard substrate communities
- Increase local biodiversity
- Maintain existing environmental diversity
- Enhance public safety
- Enhance land-use potential
- Satisfy community expectations
- None

The following ‘Other’ potential negative impacts were proposed:

- Habitat loss and replacement
- Decreased biodiversity
- Maintenance costs
- Trap and retain litter
- Promote unsustainable management strategies

The following ‘Other’ considerations for planning coastal defence works were proposed:

- Impact on commercial fisheries
- Most appropriate solution
- In-line with SMP policy
- Part of a sustainable strategy

Question 6: *How* ***supportive*** *are you of the construction of additional coastal defence structures around the UK?*
Question 7: *How* ***supportive*** *are you of the construction of additional multi-functional coastal defence structures around the UK?*

Questionnaire responses collectively indicated significantly increased levels of support for additional coastal defence structures in the UK if they were multi-functional structures (Wilcoxon Z = -7.377, $P < 0.001$) (Figure 1), and the magnitude of increase was consistent across all sectors ($F_{7,117} = 1.250$, $P = 0.282$). Respondents from the Statutory Bodies sector indicated the lowest mean levels of support for both standard (4.1 ± 0.6 SE) and multi-functional structures (5.8 ± 0.7 SE), whilst respondents from the Engineering Consultant sector indicated the highest levels of support (7.7 ± 0.8 SE and 9.0 ± 0.5 SE, respectively). The difference in support for additional (non multi-functional) coastal defence structures between these two sectors was significant ($F_{7,117} = 2.578$, $P = 0.017$; SNK $P < 0.05$).

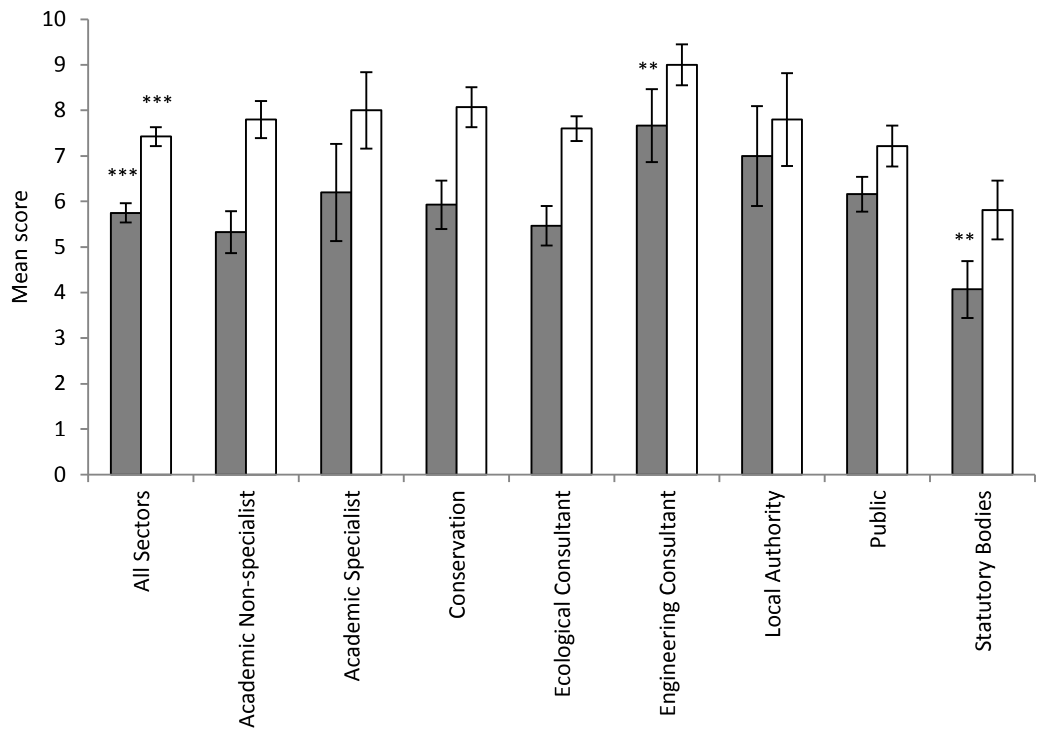

Figure 1 Level of support for additional coastal defence structures (grey bars) and additional *multi-functional* coastal defence structures (white bars), as indicated by mean scores (n = 118) assigned by questionnaire respondents on a scale of 1 – 10 (1 = 'Not supportive at all', 10 = 'Very supportive').

***Question 8: Why** would you feel more/less supportive of new coastal defences if they were multi-functional structures?*

The most frequently-selected reasons for being more supportive of multi-functional structures were 'Might as well get the most out of new developments' (59.3%), 'This would reduce the impact on the environment' (55.1%) and 'This would enhance the environment' (53.4%) (Table 6). The most frequently-selected reason for being less supportive was 'This would be more expensive' (15.3%) (Table 7).

Perceptions were consistent across sectors (Pseudo-$F_{7,113}$ = 1.310, P(perm) = 0.155). However, respondents from the Academic Non-specialist and Ecological Consultant sectors did not perceive 'This is what the government is encouraging us to do' to be a reason for being more supportive of multi-functional structures, and Academic Specialists did not perceive 'This would be more likely to get consent' as a reason to be more supportive. Many of the reasons for being less supportive of multi-functional structures were unselected by several sectors since most respondents indicated increased support for multi-functionality.

Table 6 Frequency of selection (% of responses) of reasons for being more supportive of new coastal defence structures if they were *multi-functional* structures, as indicated by questionnaire responses (n = 118). Respondents were asked to select all that apply.

REASONS FOR BEING MORE SUPPORTIVE	All Sectors	ANS	AS	C	EcC	EnC	LA	P	SB
Might as well	**59.3**	50.0	100	85.7	66.7	50.0	80.0	51.4	43.6
Reduce environmental impact	**55.1**	60.0	80.0	35.7	53.3	66.7	80.0	54.1	50.0
Environmental enhancement	**53.4**	50.0	100	35.7	53.3	100	40.0	54.1	43.6
Further scientific knowledge	**39.0**	65.0	60.0	28.6	33.3	33.3	80.0	27.0	31.3
Increase amenity value	**38.1**	40.0	80.0	42.9	20.0	83.3	40.0	37.8	18.6
Good for the economy	**22.9**	25.0	20.0	35.7	6.7	66.7	40.0	16.2	18.6
Alternative income opportunities	**22.0**	25.0	20.0	42.9	13.3	33.3	20.0	21.6	6.3
More likely to get consent	**13.6**	10.0	0	14.3	13.3	16.7	40.0	10.8	18.6
Encouraged to do so by government	**7.6**	0	20.0	7.1	0	16.7	20.0	5.4	18.6

Table 7 Frequency of selection (% of responses) of reasons for being more supportive of new coastal defence structures if they were *multi-functional* structures, as indicated by questionnaire responses (n = 118). Respondents were asked to select all that apply.

REASONS FOR BEING LESS SUPPORTIVE	All Sectors	ANS	AS	C	EcC	EnC	LA	P	SB
More expensive	**15.25**	20.0	20.0	0	6.7	33.3	0	16.2	25.0
Increase environmental impact	**8.47**	10.0	20.0	7.1	0	0	0	8.1	18.8
Compromise function	**7.63**	0	20.0	0	6.7	16.7	0	10.8	12.5
Not their purpose	**3.39**	0	0	0	0	0	0	5.4	12.5
Public risk	**3.39**	0	20.0	0	0	0	0	5.4	6.3
Reduce amenity value	**1.69**	0	0	7.1	0	0	0	2.7	0
Indifferent	**1.69**	5.0	0	0	0	0	0	2.7	0

The following 'Other' reasons for being more supportive were proposed:

- This would foster community support
- This would provide opportunities for education and outreach
- This would add value to the development
- Novel habitat would partially compensate for negative environmental impacts
- This would enhance public safety
- Technology exists
- This would attract partnership funding

The following 'Other' reasons for being less supportive were proposed:

- This should not be prioritised over sustainable long-term strategies

Question 9: *What type of multi-functional structure would you be* ***most supportive*** *of?*

Overall rankings indicated most support for multi-functional coastal defence structures that ‘Increase habitat complexity’, ‘Support species of conservation value’ and ‘Support natural rocky shore communities’ (Table 8). At the other end of the scale, there was least support for structures that ‘Provide a good place to go rock-pooling’ and ‘Improve surfing conditions’.

Perceptions were consistent across sectors (Pseudo-$F_{7,110}$ = 0.656, P(perm) = 0.910). However, no respondents from the Engineering Consultant sector included ‘Improve surfing conditions’ in the five most important functions, and they indicated lower support for structures that ‘Support commercially valuable species’ and ‘Provide refuge for commercial fisheries species’ than others did. Instead, they indicated higher support for structures that ‘Attract more tourists to the area’. Local Authority respondents also favoured this secondary function over others, but none from this sector prioritised structures that ‘Provide a good place to go rock-pooling’. In contrast, the Academic Specialists indicated a reasonably high level of support for this function.

Table 8 Types of multi-functional structures most supported, as indicated by combined ranks of questionnaire respondents and by combined ranks of respondents from different sectors. Respondents were asked to rank 5 options on a scale of 1 to 5 (1 = most important, 5 = least important).

n/s: not selected

SECONDARY FUNCTIONS	All Sectors	ANS	AS	C	EcC	EnC	LA	P	SB
Increased habitat complexity	1	1	2	1	2	1	1	2	2=
Habitat for conservation species	2	3	1	2	1	2	2=	1	2=
Habitat for rocky shore communities	3	2	3	3	3	4	4	3	1
Opportunities for research & education	4	4	5	4	5	5	5	4	4
Habitat for commercial species	5	5	6	5	6	7=	6=	5	5
Refuge for exploited species	6	8	7	6	4	9	8=	7	6
Enhanced tourism	7	6	9=	8	9=	3	2=	6	8=
Enhanced recreational fisheries	8	7	8	7	8	6	6=	10	7
Enhanced surfing conditions	9	10	9=	10	7	n/s	8=	8	10
Access for rock-pooling	10	9	4	9	9=	7=	n/s	9	8=

The following ‘Other’ types of multi-functional structures were proposed:

- One that provides opportunities for education and outreach
- One that mimics the natural local environment
- One that incorporates positive feedback into the defence function
- One that requires minimal maintenance
- One that is innovative and applicable to a range of situations
- One that maximises habitat
- One that benefits the local community
- One that increases local natural species diversity
- One that uses natural materials